# Comparing high-tech urban agriculture to conventional agriculture in Canada

**Estefany Cabanillas**

Under the Supervision of Dr. Benjamin Goldstein

Bioresource Engineering

McGill University

April 2024

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree:

**Master of Science (MSc)**

Department of Bioresource Engineering

Faculty of Agricultural and Environmental Sciences

Macdonald Campus of McGill University

Ste-Anne-de-Bellevue, Quebec, CA

## Abstract

This thesis investigates the environmental impacts of controlled-environment urban agriculture (CE-UA) in Canada, focusing on high-tech urban lettuce farming as a case study. Given the projections indicating a global population increase to 9.7 billion by 2050, and over 70% of people residing in urban areas, the pressure on food systems, exacerbated by urbanization, necessitates sustainable solutions. Agriculture already contributes significantly to environmental pressures, with cities playing a notable role due to their population density and consumption patterns. CE-UA holds promise in mitigating the environmental impacts of food production and enhancing food system resilience.

The expanding population, the effects of climate change, and dietary transitions towards higher consumption of meat, fruits, and vegetables are setting pressure on current food production technologies. To address these challenges, this study assesses the environmental performance of lettuce production with CE-UA in different Canadian regions with diverse energy grids. By analyzing factors such as carbon emissions, water usage, and land efficiency, this research provides insights into the comparative advantages and disadvantages of CE-UA over conventional agriculture.

Through a comprehensive review of the literature and empirical analysis, this study identifies key factors influencing the environmental footprint of CE-UA. It finds that while CE-UA can offer environmental benefits such as reduced water use and land use compared to conventional agriculture, its performance hinges on energy sources. Like Alberta, regions with carbon-intensive energy grids may see higher carbon emissions from CE-UA lettuce production

compared to market-average lettuce. In contrast, areas with renewable energy, like Quebec, could achieve comparable or lower emissions. Furthermore, the study highlights the importance of deploying CE-UA in conjunction with low-carbon energy sources to realize its potential for sustainable food production.

In conclusion, this thesis underscores the significance of understanding the environmental implications of CE-UA, particularly in the context of Canada's diverse energy landscapes and climatic conditions. By shedding light on the environmental performance of CE-UA and identifying areas for improvement, this study contributes to the ongoing discourse on sustainable urban agriculture and food system resilience.

## Resumé

Cette thèse examine les impacts environnementaux de l'agriculture urbaine en environnement contrôlé (CE-UA) au Canada, en se concentrant sur la culture urbaine de la laitue à haute technologie comme étude de cas. Étant donné les projections indiquant une augmentation de la population mondiale à 9,7 milliards d'ici 2050, et plus de 70% des personnes résidant dans des zones urbaines, la pression sur les systèmes alimentaires, exacerbée par l'urbanisation, nécessite des solutions durables. L'agriculture contribue déjà de manière significative aux pressions environnementales, les villes jouant un rôle notable en raison de leur densité de population et de leurs modèles de consommation. CE-UA offre des promesses pour atténuer les impacts environnementaux de la production alimentaire et renforcer la résilience des systèmes alimentaires.

L'expansion démographique, les effets du changement climatique et les transitions alimentaires vers une consommation accrue de viande, de fruits et de légumes mettent la pression sur les technologies actuelles de production alimentaire. Pour relever ces défis, cette étude évalue les performances environnementales de la production de laitue avec CE-UA dans différentes régions canadiennes avec des réseaux énergétiques diversifiés. En analysant des facteurs tels que les émissions de carbone, l'utilisation de l'eau et l'efficacité des terres, cette recherche fournit des aperçus sur les avantages et les inconvénients comparatifs de CE-UA par rapport à l'agriculture conventionnelle.

Par le biais d'une revue exhaustive de la littérature et d'une analyse empirique, cette étude identifie les principaux facteurs influençant l'empreinte environnementale de CE-UA. Elle

constate que, bien que CE-UA puisse offrir des avantages environnementaux tels qu'une utilisation réduite de l'eau et des terres par rapport à l'agriculture conventionnelle, ses performances dépendent des sources d'énergie. Par exemple, les régions comme l'Alberta, avec des réseaux énergétiques intensifs en carbone, peuvent connaître des émissions de carbone plus élevées de la production de laitue CE-UA par rapport à la laitue moyenne du marché. En revanche, les zones disposant d'énergies renouvelables, comme le Québec, pourraient atteindre des émissions comparables ou inférieures. De plus, l'étude met en évidence l'importance de déployer CE-UA en conjonction avec des sources d'énergie à faible émission de carbone pour réaliser son potentiel de production alimentaire durable.

En conclusion, cette thèse souligne l'importance de comprendre les implications environnementales de CE-UA, notamment dans le contexte des paysages énergétiques et des conditions climatiques diversifiés du Canada. En éclairant les performances environnementales de CE-UA et en identifiant les domaines à améliorer, cette étude contribue au discours continu sur l'agriculture urbaine durable et la résilience des systèmes alimentaires.

## Acknowledgments

I want to extend my heartfelt gratitude and appreciation to my thesis supervisor, Associate Professor Dr. Benjamin Goldstein., for his constructive and amiable collaboration on this work and to my thesis advisor, Assistant Professor Dr. Mark Lefsrud, for securing the funding for this research provided by the Natural Sciences and Engineering Research Council of Canada - NSERC and MITACS Inc. Your efforts have made this study possible, and I am truly thankful. I am also thankful to Benjamin and Mark for their patient guidance, encouragement, and invaluable feedback throughout this journey. Your support has been instrumental in making this thesis a rewarding experience. I would also like to acknowledge Dr. Ebenezer Kwofie for his contributions to the review of this thesis and the published paper included herein.

Furthermore, I am grateful to my roommate, Madison, whose companionship made my two years in Montreal unforgettable. To the SURF Lab, Felicity, Sadie, and Will thank you for your help and friendship and for sharing the journey. Finally, I wish to convey my deepest appreciation to my beloved parents, sisters, and friends for their unwavering support throughout this endeavor. Your encouragement has been my constant source of strength and inspiration.

## Explanation of Thesis Format

This thesis is submitted in the format of papers suitable for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies at McGill University, and follows the conditions outlined in the Guidelines Concerning Thesis Preparation, which are as follows:

"As an alternative to the traditional thesis format, the dissertation can consist of a collection of papers of which the student is an author or co-author. These papers must have a cohesive, unitary character making them a report of a single program of research. The structure for the manuscript based thesis must conform to the following:

1. Candidates have the option of including, as part of the thesis, the text of one or more papers submitted, or to be submitted, for publication, or the clearly duplicated text (not the reprints) of one or more published papers. These texts must conform to the "Guidelines for Thesis Preparation" with respect to font size, line spacing and margin sizes and must be bound together as an integral part of the thesis. (Reprints of published papers can be included in the appendices at the end of the thesis.)
2. The thesis must be more than a collection of manuscripts. All components must be integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges between the different papers are mandatory.
3. The thesis must conform to all other requirements of the "Guidelines for Thesis Preparation" in addition to the manuscripts.

The thesis must include the following:

(a) A table of contents

(b) An abstract in English and French

(c) An introduction which clearly states the rational and objectives of the research

(d) A comprehensive review of the literature (in addition to that covered in the introduction to each paper)

(e) A final conclusion and summary

1. As manuscripts for publication are frequently very concise documents, where appropriate, additional material must be provided (e.g. in appendices) in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported in the thesis.

2. In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contributions of Authors" as a preface to the thesis. The supervisor must attest to the accuracy of this vi statement. Since the task of the examiners (reviewers) is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the co-authored papers".

## Contributions of Authors

**Chapters 3** of this thesis have been prepared for publication in peer-reviewed journals. The author of this thesis was responsible for data collection, curation, life cycle assessment (LCA) systems, and the writing and editing of the published article included herein. The thesis supervisor, Dr. Benjamin Goldstein, contributed to the LCA systems, outline structure, review, and editing of the included article. Dr. Mark Lefsrud contributed to the review and feedback process of the constituent parts of the present manuscript.

# Table of Contents

# List of Figures

## List of Tables

## Acronyms and Abbreviations

| | |
|---|---|
| AFOLU | Agriculture, Forest, and Other Land Use |
| ALCA | Attributional Life Cycle Assessment |
| AWARE | Available WAter REmaining |
| CEA | Controlled Environmental Agriculture |
| CE-UA | Controlled Environmental Urban Agriculture |
| CF | Characterization Factor |
| CLCA | Contributional Life Cycle Assessment |
| FAO | Food and Agriculture Organization |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LU | Land Use |
| N | Nitrogen |
| OF | Open Field |
| P | Phosphorus |
| UA | Urban Agriculture |
| WRD | Water Resource Depletion |
| WS | Water Scarcity |
| WU | Water Use |

# Chapter 1: Introduction

## 1.1 Problem Formulation

The United Nations (2018) predicts that the global population will reach 9.7 billion by 2050, with around 7 billion of the total population living in cities. Globally, over 50% of the global population lives in urban areas today, and is expected to increase by 70%, moreover global food production is estimated to rise by 30% (Alexandratos & Bruinsma, 2012). Urbanization intensifies stresses on the planet as processes like industrialization, rising wealth, and increased consumption collectively worsen environmental degradation, resource depletion, and global challenges. The global food system causes, directly and indirectly, between 20% and 30% of total anthropogenic environmental pressures, with cities, by their population and wealth, being significant contributors (Goldstein et al., 2017; FAO, 2017). This environmental impact is exacerbated by the expansion of agriculture, one of humanity's most significant environmental influences, transforming habitats and squeezing out wildlands by converting them into agricultural land. The impending global population growth and urbanization necessitate sustainable food production to mitigate potential consequences.

Agricultural practices exacerbate multifaceted challenges, encompassing diminishing arable land, biodiversity loss, water scarcity, extreme weather events, and environmental pollution. This collective predicament substantially threatens food security and global food systems' broader sustainability. The present food system exhibits a significant footprint, covering more than half of the world's habitable land. However, 37.6% of this land is allocated for actual crop cultivation, as highlighted by the Food and Agriculture Organization (FAO), which classifies 4,889 million hectares as ‘agricultural area’ out of the world’s total land area of 13,003 million hectares (Ritchie & Roser, 2019). In addition, 70% of the world’s freshwater use is directed toward agricultural use (Poore & Nemecek, 2018; Ritchie & Roser, 2022; Harris et al.,2020; FAO, 2017). This allocation of resources underscores the environmental impact of current agricultural practices, emphasizing the urgency of reevaluating and restructuring our approach to food production.

The global food supply chain’s intricate network exacerbates food waste, nutrient loss, and environmental challenges (Mohareb et al., 2017). This vulnerability is evident, especially in the COVID-19 pandemic, exposing the fragility of globalized markets. Recent challenges have underscored concerns about food production, processing, distribution, and demand (Aday & Aday, 2020). Movement restrictions, changes in consumer demand, closures of production facilities, trade constraints, and financial pressures have worsened the situation. Ensuring uninterrupted food flow requires collaborative efforts from stakeholders. Consumer confidence is crucial for food safety, as highlighted by the FAO (2020). The Organization for Economic Co-operation and Development (OECD) in 2020 emphasized that food security during crises depends more on consumer access than mere availability (2020)

The burgeoning global population and the increasing strains on resources necessitate a concerted effort to develop sustainable agricultural practices that address these critical challenges. As highlighted by Seto & Ramankutty (2016), while urbanization concentrates populations, fostering diverse food choices and habits, it poses challenges such as the potential loss of croplands and shifts towards diets that consume more animal products and are more environmentally intensive. The intersection of urbanization and food systems underscores the need for interdisciplinary research to unravel these complex linkages and inform strategies promoting sustainable and resilient food systems in urbanized societies.

Increased acknowledgment of the links between cities and food sustainability has led to recognizing the potential of urban agriculture, especially high-tech urban greenhouses (GH), and controlled environmental agriculture (CEA) systems, to grow food locally with lower environmental impacts. These technologies promise to maximize space, increase crop yields, and curtail resource consumption, addressing pressing environmental and food security concerns (Kozai, 2013). Hydroponic CEA in urban areas is a technology that can shorten supply chains by reducing transportation and is argued to enhance resilience by reconnecting producers and consumers within local markets. Such a shift, encapsulated in the concept of 'hyper-localism,' not only addresses environmental concerns but also aligns with efforts to mitigate food loss and waste. It is estimated that one-third of food produced is lost or wasted each year, totaling about 1.3 billion tons and accounting for 8–10% of total annual GHG emissions (Casey, et al., 2022; Wunderlich & Martinez, 2018). In 2019, a research conducted by the Canadian government on waste management revealed that approximately 58% (equivalent to 35.5 million tonnes) of the total food produced in Canada is lost or wasted annually. This includes nearly one-third (with an estimated value of $49.5 billion) that could have been avoided.

Despite the perceived abundance of current resources, global challenges like social conflicts, unequal food distribution, waste, natural disasters, and climate change threaten food security (FAO, 2017). Innovative methods in the agricultural industry are needed to address this demand (Mousavi et al., 2022). High-tech urban agriculture, particularly CEA, shows promise in optimizing spatial utilization, enhancing yields, and streamlining supply chains for improved food security and sustainability (Kozai, 2019; MacRae, 2016). However, it's essential to recognize that the benefits of CEA come with notable energy intensity.

CEA, encompassing vertical farms and plant factories, emerges as a promising technology for ecologically friendly and intensified food production, particularly in urban settings grappling with the high environmental and economic costs of transporting power, water, and food over long distances. Environmental impacts of CEA can be mitigated through strategies like carbon-neutral energy supply, water recapture, and recycling, as well as utilizing existing structures and minimizing spoilage during transportation. CEA's environmental benefits include providing healthy, chemical-free organic food, reducing fossil fuel use, and sometimes employing sustainable energy sources like solar panels and wind turbines. The closed nature of specific CEA systems enhances environmental sustainability by minimizing reliance on external factors, decreasing exposure to pesticide use, and facilitating controlled nutrient circulation, significantly reducing phosphorus (P) and nitrogen (N) pollution. Despite these advantages, the scaling-up of CEA is challenged by technological, economic, and societal constraints (Cowan et al., 2022).

The surge in scholarly attention towards CEA is evident through approximately 18,800 results on Google Scholar from review articles in the last decade, as highlighted by a scoping review conducted by Dsouza et al. (2023). This review systematically analyzed peer-reviewed literature, revealing 1163 studies related to CEA, predominantly focusing on technical, biological, and environmental aspects. However, more socio-economic research is needed in this domain. Additionally, the findings from a meta-analysis study conducted by Gargaro et al. (2023) shed light on crucial factors influencing the growth of CEA. This study revealed a vast research landscape within the CEA industry, with 3,706 publications initially identified and 121 papers meeting inclusion criteria, resulting in only 979 relevant observations. Despite this extensive academic engagement, a significant gap exists in understanding CEA's performance in Canada, particularly regarding its environmental impacts and potential trade-offs across dimensions.

The expanding global urban, indoor, and warehouse agricultural operations further underscores CEA's growing interest. For instance, in the United States, the number of such operations surged from 15 to 56 between 2015 and 2017 (Newbean Capital, 2017). Similarly, in Japan, the commercial production of leaf vegetables in plant factories with electrical lighting increased significantly from 35 in 2009 to 106 in 2011 (Kozai, 2013). The trend is not limited to specific regions, as evidenced by Asia's substantial presence in CEA, with over 518 plant factories reported by the end of 2016, along with several commercial container-style farms in various stages of development (Newbean Capital, 2016). These global developments underscore the interest and need for comprehensive research and understanding of CEA's implications, including its environmental impacts and socio-economic dynamics.

Characterizing these impacts is essential to ensuring that CEA is environmentally desirable. What if food from CEA is more resource or GHG-intensive than conventional agriculture? For example, Martin et al. (2023) conducted a life cycle assessment of a large commercial vertical farm in Sweden producing packaged lettuce, comparing its environmental performance with conventional imported and domestically produced lettuce. The results indicated lower GHG emissions from the CEA but potentially larger environmental impacts in other categories due to significant electricity demand, highlighting electricity use as a key hotspot, including electricity use, packaging, infrastructure, and product distribution. Similar findings were observed in another study by Casey et al. (2022), which assessed hydroponic CEA systems. Despite using approximately 15 kWh of electricity per kg of lettuce, CEA systems showed potential for smaller carbon footprints than most field-based supply chains. However, these benefits are contingent on using renewable energy. Additionally, CEA systems demonstrated orders of magnitude less direct water usage and potential benefits in mitigating water stress and soil degradation in arid regions. However, both studies underscored the energy intensity of CEA systems and the importance of renewable energy sources to mitigate environmental impact effectively.

Studies suggest higher environmental impacts associated with CEA compared to conventional agriculture. For instance, a study conducted in The Netherlands by Blom et al. (2022) revealed that the carbon footprint of CEA was considerably higher than that of conventional farming methods. In the baseline scenario, the carbon footprint of the CEA farm was 5.6 to 16.7 times greater than conventional farming methods, and in an alternative scenario, using renewable energies, it was 2.3 to 3.3 times higher. The study highlighted that electricity demands accounted for a significant portion of the carbon footprint, representing 85% in the baseline scenario and 66% in the alternative scenario. This indicates that a substantial reduction in electricity usage is necessary to be competitive with conventional farming methods regarding carbon footprint. However, the study also pointed out the potential benefits of CEA if these challenges are addressed. CEA has the potential to efficiently utilize land, achieve high yields, minimize water usage, and reduce the need for pesticides and herbicides. Moreover, its ability to be situated within or near urban areas can contribute to food security and sustainability.

These findings highlight the need for comprehensive life cycle assessments (LCA) to fully understand the environmental implications and performance of CEA practices across different energy source scenarios and supply chain configurations, particularly in contexts like Canada, where energy grids and environmental considerations may differ and be able to identify areas for improvement. Furthermore, the reduced direct water requirements of hydroponic CEA systems compared to conventional open field (OF) systems make them crucial in mitigating the vulnerability of food supply to future water stress, particularly in regions already grappling with water scarcity. While recognizing the potential of CEA systems in building resilient food supply chains, it is essential to consider their geographic applicability and potential upstream impacts on water stress in regions supplying components for renewable energy and battery systems (Casey et al., 2022).

The study's focus on Canada is intricately tied to the significant challenges facing the country's agricultural sector, particularly within the greenhouse industry. According to the Government of Canada (2021), chronic labor shortages persist throughout Canada's agricultural landscape, with the greenhouse sector notably struggling to fill positions, representing a substantial portion of the industry's workforce gaps. The vulnerability of this sector to labor shocks was starkly exposed during the COVID-19 pandemic, highlighting the pressing need for innovative solutions to bolster productivity and mitigate reliance on manual labor. Additionally, projections from the Canadian Agricultural Human Resource Council (CAHRC) indicate a forthcoming increase in global demand for Canadian agricultural products, necessitating adjustments to production levels and workforce productivity. Given these circumstances, the study zooms in on Canada as the perfect setting to explore how CEA systems perform environmentally and their potential advantages.

### 1.2 Knowledge Gaps

Hydroponic CEA systems have been environmentally evaluated in diverse regions such as Sweden (Martin & Molin, 2018), Arizona (Barbosa et al., 2015), and France (Romeo et al., 2018). Romeo et al. (2018) found hydroponic CEA systems more efficient over open-field and heated greenhouse systems, with energy consumption identified as a primary concern that could be mitigated through renewable energy adoption. However, these studies primarily relied on local grid mix electricity emission factors and local system comparisons, overlooking long-distance supply chains. This literature gap underscores the necessity for a comprehensive LCA comparing CEA with large-scale open-field agriculture across various supply chain setups. Despite the potential of CEA, significant knowledge gaps persist in fully assessing its environmental impacts, particularly within the Canadian context. Existing research often concentrates on specific geographical areas, failing to capture the diversity of energy systems and environmental conditions across different regions, hindering the extrapolation of findings to other Canadian cities and climates.

A critical void in research exists concerning the potential trade-offs between the advantages of CEA and its substantial energy burdens, particularly in vast countries like Canada, which are characterized by diverse energy grids and climates. CEA systems present a promising solution for sustainable food production but face environmental trade-offs, with energy requirements being a key challenge. The primary disadvantage lies in the carbon footprint associated with the energy use in CEA systems. Although some systems, like glasshouse horticulture, may not heavily rely on electricity, the full potential necessitates electrical lighting and temperature control, contributing to carbon emissions (Cowan et al., 2022). Mitigation strategies include utilizing solar, geothermal, or waste heat, but the global reliance on fossil fuels remains a significant hurdle (Adams et al., 2011; Teo & Go, 2021, as cited by Cowan et al., 2022).

While CEA systems focus on optimizing energy efficiency through advanced technologies, transportation-related carbon emissions also impact sustainability. In comparing CEA and conventional systems, transportation distance becomes a crucial factor. CEA's advantage lies in producing food consistently in or near urban centers throughout the year, reducing the need for long-range transportation and associated emissions. However, striking a balance between transportation and energy savings requires careful consideration, especially with evolving technologies like electric vehicles and renewable energy sources. Assessments must be case-specific, acknowledging the dynamic landscape of emerging technologies and environmental conditions.

### 1.3 Research Questions and Objectives

The main objective of this master's thesis is to compare conventional and high-tech urban agriculture across diverse Canadian provinces and climates, focusing on an indoor shipping container vertical farm using controlled environment technology. The study investigates the environmental performance of CEA under various conditions, addressing a current knowledge gap by evaluating hydroponic system performance under different energy source scenarios, encompassing a wide array of regional and international supply chains based on field production across diverse agri-climatic zones and aiming to demonstrate the environmental efficacy of urban agriculture, particularly in cities where food-related environmental impacts are more significant.

The following research questions guide this study to fulfill the aim:

- What is the environmental footprint of a shipping container CEA versus conventional vegetable supply chains producing for the Montreal market?
- What are the trade-offs across different environmental indicators in CEA?
- How does the environmental performance of CEA vary by location across the Canadian provinces and territories?

To achieve these objectives, the present study employs a life cycle assessment (LCA) methodology, adhering to ISO 14040 and 14044 (2006) standards, to compare the environmental footprints associated with lettuce production through conventional Open Field (OF) farming and Controlled Environmental Urban Agriculture (CE-UA), evaluating factors such as greenhouse gas emissions (GHG), land use (LU), and water resource depletion (WRD) aiming to provide valuable insights into the sustainability CE-UA as a food supply for Canadian cities.

The findings show that CE-UA farming systems can have significantly higher energy use and GHGs than conventional lettuce production, primarily driven by on-site energy consumption (heating and cooling, among others). However, the infrastructure can also be a significant driver of emissions if farm lifespans are short. The farm's location and the electrical grid's carbon intensity also affect GHG intensity. Water use is more in line with conventional agriculture and can be much lower per kilogram produced using CE-UA. These findings emphasize the need for careful consideration of optimal locations and sustainable practices for high-tech agriculture in urban areas, as they may only sometimes guarantee low-carbon agriculture. The limited scope and regional variations in existing studies underscore the necessity for comprehensive assessments of urban agriculture's environmental impacts, including GHG emissions, water usage, and land usage.

### 1.4 Thesis Outline

The outline of this thesis is as follows: **Chapter 1** (Introduction) presents the problem formulation to establish comprehension of the research aim and introduces the research questions guiding the study. **Chapter 2** (Literature review) provides the reader with essential information for understanding the methods chosen, encompassing all decisions made throughout the study and the conceptual framework employed for analyzing the collected data and information. **Chapter 3** (Manuscript) outlines and presents the emissions from conventional and CE-UA systems across Canada. The empirical data gathered by site visits will be exhibited, alongside an analysis of the results utilizing the conceptual framework. **Chapter 4** (Discussion) discusses the findings of the analysis and offers suggestions for future research. Lastly, **Chapter 5** (Summary and Conclusions) concludes the papers.

## References


Adams, S. R., Valdes, V. M., Langton, F. A., & Hamer, P. J. C. (2011). Reducing carbon emissions from greenhouse production through the use of temperature integration and alternative sources of heat. Acta Hortic. 95−101. doi: 10.17660/ActaHortic.2011.893.5. 10.17660/ActaHortic.2011.893.5

Aday, S., & Aday, M. S. (2020). Impact of COVID-19 on the food supply chain. Food Quality and Safety, 4(4), 167-180. https://doi.org/10.1093/fqsafe/fyaa024

Alexandratos, N., & Bruinsma, J. (2012). World Agriculture towards 2030/2050: the 2012 Revision.

Casey, L., Freeman, B., Francis, K., Brychkova, G., McKeown, P., Spillane, C., ... & Styles, D. (2022). Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and field-based supply chains. Journal of Cleaner Production, 369, 133214. https://doi.org/10.1016/j.jclepro.2022.133214

Cowan, N., Ferrier, L., Spears, B., Drewer, J., Reay, D., & Skiba, U. (2022). CEA systems: the means to achieve future food security and environmental sustainability? Frontiers in Sustainable Food Systems, 6, 891256. https://doi.org/10.3389/fsufs.2022.891256

Dalin, C., & Rodríguez-Iturbe, I. (2016). Environmental impacts of food trade via resource use and greenhouse gas emissions. Environmental Research Letters, 11(3), 035012. DOI 10.1088/1748-9326/11/3/035012

Desa, UN Department of Economic and Social Affairs (2018). Revision of world urbanization prospects. UN Department of Economic and Social Affairs, 16.

Dsouza, A., Newman, L., Graham, T., & Fraser, E. D. (2023). Exploring the landscape of controlled environment agriculture research: A systematic scoping review of trends and topics. Agricultural Systems, 209, 103673. https://doi.org/10.1016/j.agsy.2023.103673

Food and Agriculture Organization of the United Nations (FAO). (2020). Ample supplies to help shield food markets from the COVID -19 crisis. http://www.fao.org/documents/card/en/c/ca8445en

Government of Canada, Environment and Climate Change Canada (2019). Waste management in Canada. https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/food-loss-waste.html

Government of Canada, Innovation, Science and Economic Development Canada (2021). Innovative Solutions Canada: https://ised-isde.canada.ca/site/innovative-solutions-canada/en/enhancing-automation-controlled-environment-agriculture-farming

International Organization for Standardization. (2022). ISO 14040:2006 Environmental management: life cycle assessment; Principles and Framework. ISO.

Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proceedings of the Japan Academy, Series B, 89(10), 447-461. https://doi.org/10.2183/pjab.89.447

Kozai, T., Niu, G., & Takagaki, M. (Eds.). (2019). Plant factory: an indoor vertical farming system for efficient quality food production. Academic press.

MacRae, R., Siu, A., Kohn, M., Matsubuchi-Shaw, M., McCallum, D., Cervantes, T. H., & Perreault, D. (2016). Making better use of what we have: Strategies to minimize food waste and resource inefficiency in Canada. Canadian Food Studies/La Revue canadienne des études sur l'alimentation, 3(2), 145-215. https://doi.org/10.15353/cfs-rcea.v3i2.143

Martin, M., Elnour, M., & Siñol, A. C. (2023). Environmental life cycle assessment of a large-scale commercial vertical farm. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2023.06.020

Mohareb, E., Heller, M., Novak, P., Goldstein, B., Fonoll, X., & Raskin, L. (2017). Considerations for reducing food system energy demand while scaling up urban agriculture. Environmental Research Letters, 12(12), 125004. https://iopscience.iop.org/article/10.1088/1748-9326/aa889b

Mousavi, A., Aghbolaghi, E. A., Khorramifar, A., Gancarz, M., Darvishi, Y., Stasiak, M., ... & Karami, H. (2022). Life Cycle Assessment for Environmental Impact Reduction and Evaluation of the Energy Indices in Lettuce Production. Applied Sciences, 12(20), 10348. https://doi.org/10.3390/app122010348

Newbean Capital (2016). The rise of Asia's indoor agriculture industry. Retrieved from https://indoor.ag/whitepaper/

Newbean Capital (2017). Indoor crop production, feeding the future (2nd ed.). Retrieved from https://indoor.ag/whitepaper/

Poore, J., & Nemecek, T. (2018). Reducing food’s environmental impacts through producers and consumers. Science, 360(6392), 987-992. DOI:10.1126/science.aaq0216

Ritchie, H., & Roser, M. (2019). Land use. Our world in data.

Ritchie, H., & Roser, M. (2022). Environmental impacts of food production. Our world in data.

Seto, K. C., & Ramankutty, N. (2016). Hidden linkages between urbanization and food systems. Science, 352(6288), 943-945. https://www.science.org/doi/10.1126/science.aaf7439

Teo, Y. L., & Go, Y. I. (2021). Techno-economic-environmental analysis of solar/hybrid/storage for vertical farming system: A case study, Malaysia. Renewable Energy Focus, 37, 50-67. https://doi.org/10.1016/j.ref.2021.02.005

The Organisation for Economic Co-operation and Development (OECD). (2020). COVID-19 and international trade: Issues and actions. http://www.oecd.org/coronavirus/policy-responses/covid-19-and-international-trade-issues-and-actions-494da2fa/

United Nations Environment Programe (UNEP). (2014). Assessing Global Land Use: Balancing Consumption with Sustainable Supply. A Report of the Working Group on Land and Soils of the International Resource Panel. Bringezu S., Schütz H., Pengue W., O Brien M., Garcia F., Sims R., Howarth R., Kauppi L., Swilling M., and Herrick J.

## Connecting Text to Chapter 2

**Chapter 1** outlined the environmental challenges posed by the global food system, especially in urban areas, emphasizing the need for sustainable food production. It sets the stage for exploring alternative agricultural practices, notably high-tech urban agriculture like controlled environmental agriculture, as viable remedies to fortify food security and sustainability, particularly in urban locales facing environmental pressures. Subsequently, the overarching goals of this thesis are presented along with specific research questions and hypotheses. **Chapter 2** expands on this foundation by delving into the literature on global environmental impacts and intricacies within the food supply chain. Additionally, we scrutinize the details of life cycle assessment methods chosen to compare the environmental impacts of different farming methods within Canada.

# Chapter 2: Literature Review

## 2.1 Global Environmental Impacts of Agriculture

As stressed above, global food systems contribute to numerous global environmental challenges. The immediate response to the growing need for food production often involves intensified use of agrochemicals, notably chemical fertilizers and pesticides. The widespread adoption of pesticides, encompassing insecticides, fungicides, herbicides, and more, has helped curb crop losses and enhance yields across various crops and livestock. However, this has led to a continuous rise in pesticide usage globally, resulting in environmental pollution and posing risks to non-target species (Taylor et al., 2003, as cited by Carvalho, 2006). Consequently, pesticide residues pervade soils, water bodies, and food chains, ultimately exposing humans to these harmful substances through consumption.

Furthermore, the overuse of chemical fertilizers nitrogen in vegetable crop cultivation, ranging from 469 to 2000 kg $ha^{-1}$, leads to environmental issues. Conventional agriculture loses over 80% of applied nitrogen (N) and 25–75% of phosphorus (P) to the environment, contributing to environmental degradation and GHG emissions (Cowan et al., 2022). N and P are indispensable inputs for the sustainability of agriculture. Both inputs have increased dramatically in recent decades, but so have the nutrient losses, mainly as N cannot be fully utilized in any production system (Neeteson et al., 2003, as cited by Schröder, 2004). Nutrient losses have several environmental consequences; N and P losses, in particular, can negatively affect the quality of soils, groundwater, surface water, and the atmosphere (Schröder, 2004). However, this thesis will focus on three environmental indicators: climate change, land use, and water use, as these are the indicators of most interest to our industrial partner and funding agency.

### 2.1.1 Climate Change

Around half of all habitable land is currently occupied by agriculture, contributing to concerns about food security (Ritchie & Roser, 2019). The effects of climate change, including changing rainfall patterns, drought, and flooding, are exerting pressure on agricultural production. This pressure is exacerbated by the expected need to increase overall food production to 70% by 2050 to feed the growing global population (FAO, 2009; Touliatos, 2016). Climate change-related challenges threaten food security, making it necessary to work on innovative agriculture and resource sustainability approaches. The surging global demand for food has driven a twofold increase in agricultural food production over the past 35 years, primarily propelled by current agricultural intensification. This intensification involves the heightened use of N and P fertilizers, expansion of irrigated cropland, and an overall increase in land cultivation, resulting in profound environmental impacts. These impacts encompass anticipated disruptions of natural ecosystems, adverse effects on freshwater and marine ecosystems due to nutrient buildup from agriculture, and a notable contribution to the accumulation of GHGs, thereby exacerbating global climate change. Effectively addressing the challenges these changes pose requires a recalibration of sustainable practices, striking a balance between meeting the escalating global food demands and preserving vital ecosystem services (Tilman, 2001).

It is crucial to recognize that agriculture not only impacts climate change but is also susceptible to climate change, affecting both crop yields and land suitability for agriculture. Fueled by escalating GHG emissions, climate change presents a more formidable threat than in previous decades. The escalating temperatures exacerbate this threat, reducing water availability in critical regions and increasing the frequency and intensity of extreme weather events (WFP, FAO, IFRC, and OXFAM, 2009, as cited in Zhang, 2011). The repercussions of these effects are poised to become more pronounced. The impact of climate change on future global agricultural production is a matter of significant concern. The magnitude of this impact varies across regions, fluctuates over time, and is influenced by socioeconomic development paths, including technological advancements, economic growth, and policy decisions (Zhang, 2011).

### 2.1.2 Land Use

Over the past six decades, cropland conversion has increased by around 11%, contributing to the degradation of one-third of the world's land in the last 40 years due to erosion and pollution. This crisis of degraded soil poses potentially disastrous consequences as global food demand rises, emphasizing significant environmental concerns. Agriculture contributes to 23% of total anthropogenic GHG emissions, with a nearly twofold increase in emissions attributed to 'Agriculture, Forestry, and Other Land Use' (AFOLU). The AFOLU sector's carbon dioxide equivalent emissions primarily stem from LU practices, livestock production, and soil and nutrient management (IPCC, 2019; Tubiello et al., 2014, as cited by FAO, 2017).

Drawing on data from Our World in Data (2020), globally, agricultural areas encompass 37.6% of the total land area, totaling 4,889 million hectares, categorized into arable land (28%), permanent crops (3%), and permanent meadows and pastures (69%). As mentioned, above, it is projected that food demand will continue to increase, necessitating additional arable land and intensified production (Harris et al., 2020; FAO, 2009; Touliatos, 2016). However, 33% of the world's farmland experiences moderate to high levels of degradation, particularly impacting dryland areas and posing obstacles to food security (FAO, 2014). Climate change exacerbates these challenges, emphasizing the need for sustainable crop production.

### 2.1.3 Water Usage

As highlighted by Sihvonen (2021), agriculture significantly contributes to water pollution, with food production accounting for about 78% of global ocean and freshwater eutrophication by polluting waterways with nutrient-rich agricultural runoff from farms, pastures, and feedlots (Ritchie & Roser, 2022). Over the past century, global water demand has surged by 600%, reflecting a substantial increase in the need for water resources worldwide. Agriculture emerges as the most crucial water user among various sectors; as estimated by Heinke in 2020, around 4,387 km of blue and green water is utilized for livestock feed production, constituting approximately 41% of total agricultural water use. Projections suggest that by 2050 this figure may escalate to 20%-30%, translating into 5,500 to 6,000 km3 annually (Harris et al., 2020). Excessive nitrogen application in vegetable crop cultivation leads to environmental issues, with various irrigation methods influencing nitrogen losses (Jin et al., 2022). Drip irrigation, especially with a lower limit of 65%, effectively enhances crop nitrogen utilization and reduces nitrogen loss in lettuce fields (Jin et al., 2022).

Acknowledging the intricate relationship between agriculture and water resources is paramount, given water scarcity and undervaluation as a crucial economic input (Calzadilla et al., 2013). Despite increased efforts to preserve water quality and address water management issues, effective wastewater management remains lacking in many countries. Farms discharge substantial quantities of agrochemicals, organic matter, drug residues, sediments, and saline drainage into water bodies, posing risks to aquatic ecosystems, human health, and productive activities (UNEP, 2016, as cited in FAO 2017).

## 2.2 Global Food Challenges and Cities

When analyzing the emissions from any farming system, it is essential to remember that food systems are complex. The global food system is intricately connected to environmental challenges such as biodiversity loss, freshwater pollution, climate change, deforestation, and nutrient accumulation (Weidner et al., 2019). In a world experiencing rapid population growth, evolving economic development, and constrained planetary boundaries due to climate change, supplying water, food, resource destruction, and energy to burgeoning cities poses a formidable challenge to the food system (Zhong et al., 2021). Efforts to address these challenges should prioritize reducing the overuse of crop inputs and minimizing global water and nutrient usage (Mueller et al., 2012).

Over half of the global population resides in cities, where approximately 80% of all food produced is consumed. (FAO, 2020). As cities continue to grow, their demand for food increases, emphasizing the interconnectedness between urban areas and global food systems. Recognizing this link, urban agriculture has emerged as a local solution to address environmental impacts associated with global food systems. Food supply chains account for 18% of food emissions; this includes food processing, distribution, transport, packaging, and retail (Ritchie & Roser., 2022).

In response to growing urbanization, food is produced "locally" in many North American and European cities to enhance food security by shortening and thus improving the resilience of food supply chains. While it has historically been a widespread practice in developing countries, current awareness of climate change and concerns about urban food security have recently increased interest in urban farming practices in developed countries (Caputo, 2012; Hall et al., 2014, as cited by Benis & Ferrão, 2017). By localizing food production, cities can reduce transportation emissions and mitigate food waste, contributing to environmental sustainability (Mohareb et al., 2017; Jones, 2002, as cited by Benis & Ferrão, 2017). It also emerges as a potential solution with implications for energy demand, offering a pathway to enhance food security while mitigating environmental impacts (Kozai, 2013) by reducing food miles and resource use efficiency for agriculture.

Research by Kozai et al. (2019) underscores the significance of local food production and reducing transportation distances for fresh foods to improve food security and sustainability. Similarly, MacRae et al. (2016) highlight how extensive transportation of food over long distances contributes to substantial levels of food waste, attributing this to losses within complex supply chains reliant on effective cooling mechanisms. Additionally, Managa et al. (2018) quantified the postharvest losses, changes in phytochemicals, and loss of minerals in lettuce. They observed a notable reduction in ascorbic acid, total chlorophyll content, and carotenoids in lettuce heads retrieved at the retail shelf point. This underscores the impact of prolonged transportation and storage on the nutritional quality of produce. According to findings from York University (n.d.), the extended period between harvest and consumption, particularly evident in Canada, where fruits and vegetables imported from California can experience transit times of 5-10 days, may result in significant nutrient losses, ranging from 30-50%.

However, rising demand complicates distribution systems and necessitates resilient food production techniques closer to consumers, especially in the face of supply chain shocks like the COVID-19 pandemic, as Martin et al. (2023) discussed. Understanding the energy footprint is crucial, encompassing direct and indirect energy resources for producing goods and services throughout the supply chain. This assessment can be conducted at various global, national, regional, local, industrial, and product levels (Iñaki et al., 2016). One approach to accomplish this goal involves minimizing food miles, denoting the distance food travels from production to consumption, directly influencing the energy footprint (Coley et al., 2009).

## 2.3 Urban Agriculture

### 2.3.1 What is urban agriculture?

Urban agriculture (UA) emerges as a solution to mitigate traditional food production's adverse environmental impacts by leveraging local resources and simplifying distribution chains (Yan et al., 2022). Positioned as a crucial urban component, it can address food insecurity and environmental degradation challenges. By streamlining the supply chain, UA offers a more efficient means of meeting local food demands. Sustainable practices within UA can potentially diminish the need for storing and transporting imported products and reduce water usage through sustainable irrigation and recycling (Mohareb et al., 2017; Nogeire et al., 2018; McDougall, 2018). However, studies indicate that urban farms may still contribute to increased energy and water consumption (Mohareb et al., 2017).

UA can produce spans a range of goods for local consumption, including grains, fruit, vegetables, meat, poultry, honey, and dairy products (McDougall et al., 2018; Enthoven, 2021). The scale of UA can vary from small to medium or large, and it can operate on a commercial, community, or residential level. It may occur indoors or outdoors, with models such as commercial farms, community gardens, indoor vertical farms, greenhouses, and rooftop gardens (Opitz et al., 2016). UA is an opportunity to enhance food supply, health, local economies, social integration, and environmental sustainability, with manifestations worldwide in diverse farming systems (Orsini et al., 2013). Its popularity has been growing to foster sustainable urban development and agri-food sustainability (Tapia et al., 2021).

UA employs various techniques to cultivate food in controlled environments, encompassing greenhouse facilities, basements, and vertical farming. Goldstein et al. (2014) categorize urban agriculture into four distinct types based on their attributes, as outlined in Table 2.1. The classification considers whether the farm is physically attached to a building or ground (Building-integrated or Ground-based) and whether it utilizes CEA technologies to control lighting, $CO_2$, and temperature (Conditioned or Non-conditioned).

**Table 2.1:** Urban Agriculture typology *(Goldstein et al., 2014)*

| Attribute | Description | Example |
|---|---|---|
| Building-integrated-conditioned (BI-C) | Building base farms utilizing conditioned technologies to control the performance | Shipping container farms and indoor vertical farms |
| Building-integrated-non conditioned (BI-NC) | Building base farms with low or without conditioned technologies. | Rooftop greenhouses and indoor farming |
| Ground-based-conditioned (GB-C) | Standalone farms utilizing conditioned technologies | Greenhouse |
| Ground-based-non-conditioned (GB-NC) | Standalone farms with low or without the help of conditioned technologies | Community gardens and green walls |

### 2.3.2 Controlled Environmental Agriculture (CEA)

CEA emerges as a sustainable solution designed to address agricultural challenges through an energy-intensive system that integrates various technologies. This method involves the utilization of data analytics to establish optimal conditions for leafy greens' production to reduce pests or disease, increase efficiencies, be more sustainable, increase yield, or save costs, adjusting factors such as heating, lighting, humidity, nutrients, and $CO_2$ levels (Kozai et al., 2019; Avgoustaki & Xydis, 2020; IISD, 2022). The goal is to maintain optimal growing conditions for food crops while optimizing resource utilization, particularly water and soil. CEA usually comes in multiple forms: container farms, greenhouses, and plant factors/vertical farms. These facilities usually use aeroponic, hydroponic, and aquaponic soilless growing methods. Irrespective of form, CEA is typically assumed to provide numerous benefits over conventional agriculture.

Vertical farming (VF) systems can be broadly divided into two categories: those comprising multiple levels of traditional horizontal growing platforms and those where the crop is grown on a vertical surface—for example, building-based vertical farms in warehouses, greenhouses, and shipping containers. Freight Farms, for example, is a vertical farm in a 40-foot shipping container originating from Boston, USA, with a one-floor stacked bed design (Engler & Krarti, 2021). CEA vertical farms can be installed in any indoor or outdoor space, such as skyscrapers, shipping containers, and basements. For example, AeroFarms in the USA is one of the largest indoor farms that provides aeroponic growing systems to produce plants without sun or soil by controlling the effectuated growing conditions with CEA. Another example is Sky Greens (Singapore) vertical farming technique in which the vegetables are planted on rotating shelves from the bottom to the top throughout the day to deliver sunlight and water for growing plants (Zaręba et al., 2021)

There are undeniable advantages to this practice. Some research has shown that it can reduce water needs by 95% (Stein, 2021; Avgoustaki & Xydis, 2020). The conditions of indoor settings significantly reduce the need for pesticides. It has also been alleged that it may reduce agricultural land use by allowing agricultural growth without expansion and making it possible to cultivate year-round independently of weather conditions. (IISD, 2022). CEA crops' growth, yield, and quality are consistently much higher than OF cultivation, and the reliability of harvests throughout the year is virtually guaranteed.

CEA should consider the temperature, lighting, ventilation, dehumidification enclosed crop conditions. Heating, ventilation, and air conditioning (HVAC) systems furnish the essential conditions to maintain the indoor environment at an optimal level conducive to plant growth.

Light conditions and air temperature are the two most critical environmental factors for plants' growth (Shamshiri et al., 2018). Usually structured and insulated in a closed plant production system using electrical lighting as the only source of light for better density, period, and light intensity control over the operation (Engler & Krarti, 2021; Shamshiri et al., 2018). An essential application of CEA in the greenhouse includes $CO_2$ management. To maintain a given $CO_2$ concentration within the greenhouse, the supply must balance the assimilated $CO_2$ flux to the outside air due to ventilation. An efficient greenhouse requires environmental control for air quality, disease reduction, pest control, and nutrient and water uptake (Shamshiri et al., 2018).

In addition, they can facilitate the production of high-value crops with a higher yield than those obtained from conventional agriculture by efficiently utilizing resources such as water, nutrients, space, and time, thereby potentially reducing the carbon footprint (Rajan et al., 2019). Several benefits are associated with CEA systems, although the industry is not free of challenges. From an economic perspective, controlling the environment results in a stable supply chain, price stability, long-term contracts with distributors and retail markets, and high yields per square foot. According to Rajan (2019), this method has many advantages over conventional farming methods, including:

- Reduction in water usage: controlled environments and efficient irrigation systems have reduced water consumption considerably.
- Reduced use or elimination of pesticides and fertilizers: can be designed to use organic pest control and fertilization methods, which reduces the amount of

chemicals used, by the effective use of nutrients inputs and other synthetic chemicals.

- Year-round production: can be done indoors all year round, which allows for a continuous supply of fresh produce.
- Increased crop yields: can produce yields up to 10 times higher.
- Less land usage: using limited space, these farms can be built using small spaces like rooftops, abandoned warehouses, or shipping containers.

### 2.3.3 CEA Claim and Support #1 - Energy and Carbon

Energy consumption is a significant factor contributing to GHG emissions and global warming. Key gases released by agricultural production include carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). As global stakeholders strive to propose and implement innovative techniques for identifying and reducing GHGs, it becomes imperative to scrutinize emissions across different farming types and propose sector-specific mitigation measures (Avgoustaki, 2020).

In conventional farming, energy usage is closely tied to fossil fuels for soil plowing, sowing, fertilization, and harvesting. Additionally, substantial electricity is required for water irrigation, constituting up to 20% of total fossil fuel usage in developed countries (Despommier, 2010). However, CEA prioritizes automation and precision agriculture, meticulously measuring and validating input resources to optimize crop cultivation efficiently. It has been claimed that CEA requires 82 times more energy, with heating and cooling being the primary culprits compared to conventional farming practices (Barbosa et al., 2015). CEA facilities report an annual energy consumption of 17,382.4 kWh, with lighting accounting for nearly 70-80% of the annual electricity cost for energy use, while air conditioning accounts for around 16-28%, and auxiliary electrical equipment demands approximately 4% of the electricity (Avgoustaki et al., 2020; Engler & Krarti, 2021).

### 2.3.4 CEA Claim and Support #2 - Water

CEA can significantly reduce water usage by employing soil-less growing systems, including aquaponics, hydroponic, and aeroponics. Inputs and outputs in CEA farms amount to only 2.4%-4.8% of the water required for growing lettuce using conventional open-field methods (Stein, 2021). As studied by Beacham et al. (2019), greenhouse production of lettuce uses 0.08 GWh/ton, while field-grown salads require 0.0014 GWh/ton. Compared to conventional field production, a hydroponic greenhouse demonstrates a ten times higher yield and a ten times smaller water requirement, ultimately saving approximately 70-95% of water (Kürklü et al., 2018; Beacham et al., 2019). Hydroponic CEA's ability to optimize water usage, especially compared to conventional OF methods, that showcases its potential as an efficient and sustainable agricultural approach.

### 2.3.5 CEA Claim and Support #3 - Nutrients and other agri-chemicals

CEA farming technology usually encompasses the soil-less cultivation of plants, utilizing a nutrient solution, mainly inorganic fertilizer, applied to the plants through a soil-less medium (Rajan et al., 2019). Hydroponics, a key component of this technology, offers a notable advantage over conventional agriculture, providing enhanced control over crop nutrition, improved nutrient regulation, and water management, as highlighted by Majid et al. in 2021. CEA utilizes culture beds isolated from soil, where a nutrient solution, enriching the irrigation water, is efficiently distributed to the plants through a pumping system. The highly automated irrigation process facilitates the drainage of the nutrient solution from the culture beds, which is then returned to the central nutrient solution tank for recycling and reuse, creating a closed-loop system (Avgoustaki & Xydis, 2020).

CEA technologies also play a pivotal role in reducing reliance on external inputs, such as pesticides, heavy machinery, and other elements harmful to the environment (Zhang et al., 2018). Adopting these techniques enhances nutrient management and aligns with sustainable agricultural practices (Stein, 2021).

### 2.3.6 CEA Claim and Support #4 - More resilient supply chain

As urban areas expand, the need for secure food sources becomes critical. CEA in urban settings (CE-UA) offers a sustainable solution to provide urban populations with a reliable food supply and address the challenges of urban food security. CE-UA provides a locally sourced alternative that reduces dependence on vulnerable external supply chains. Recent studies emphasize the worldwide consequences of losing agricultural land, especially in the context of climate change. Climate change is expected to make agricultural systems more vulnerable, increasing pressure on food delivery.

A case in point is Sweden, which faced significant droughts during the summer of 2018, impacting its food supply and highlighting the need for flood resilience. Urban centers in Sweden are not only expanding their physical footprint and population but also becoming more dependent on imported food and fossil fuels in agriculture. This situation underscores the necessity for innovative techniques and processes to secure food supplies in a changing climate (Martin & Molin, 2019).

## 2.4 Knowledge Gaps

### 2.4.1 Lack of Primary Data

Filling critical knowledge gaps is imperative, particularly in the environmental comparison of shipping container CEA vertical farms and conventional OF in Canada where primary data, especially from OF, remains limited. This context needs more information concerning GHG emissions, water use, and nutrient consumption. Despite being advocated as a sustainable food supply method, there is a dearth of environmental analyses of these farms in scholarly literature, and there is a lack of scientific evidence, particularly from large-scale commercial vertical farms, possibly due to the novelty of these systems (Martin et al., 2023). This gap in understanding impedes efforts to comprehensively assess the environmental impact of such farming methods.

The lack of comprehensive data on agricultural production in Canada poses challenges in quantifying the continent's potential contribution to global GHG emission mitigation. Additionally, deficiencies in supply chain data further challenge the understanding of food supply networks, particularly in cities that depend on extended supply chains with unclear specifics. Establishing the link between urban demand centers and production locations becomes crucial to grasping the regional nuances in the environmental impacts of CE-UA container farms compared to conventional production methods. Unfortunately, environmental risks and challenges in these supply chains have been largely overlooked, creating significant research gaps.

Beyond data limitations, a further hurdle is harmonization in defining UA. The diversity of CEA within the UA landscape introduces complexity, making it challenging to neatly categorize every example of urban agriculture. Various types of urban farming, incorporating innovations and technology for environmental control through automation, are being tested globally. This lack of a standardized definition hampers efforts to understand and precisely categorize the different segments within urban agriculture. Figure 2.1. illustrates the diverse types of urban farming and the environmental control mechanisms employed to navigate this complexity. Addressing these knowledge gaps is essential to inform comprehensive research and strategies in UA.

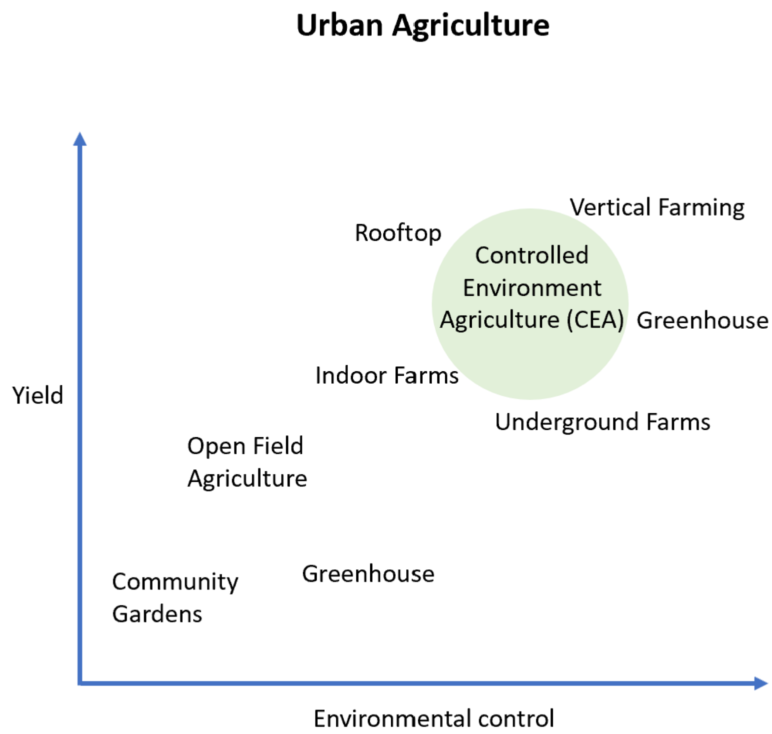



**Figure 2.1:** Urban agriculture models by yield efficiency andcc environmental control

### 2.4.2 Impacts from Infrastructure

Recent research has unveiled a more nuanced understanding of the sustainability benefits of UA endeavors, challenging initial optimism. This section elucidates the most critical drivers, offering valuable insights for future research, urban planning, and policymaking. It is important to note that LCA studies comparing UA and its conventional counterpart vary in scope. Some studies include structural components when known for both systems, while others focus solely on the operational footprint (e.g., inputs, climate control, distribution). Given that much of the infrastructure for conventional systems is already in place, comparing based on purely operational footprints mitigates accounting ambiguities to some extent. When comparing remote food supply to urban production, the impact of food miles is typically factored into the assessment. However, it is crucial to acknowledge the assumed boundaries of each LCA study cited in this section, as different studies employ varying boundaries that require careful consideration when comparing results.

Greenhouses, characterized by their controlled environment, involve intricate trade-offs. Stanhill (1980) examined the energy intensity per unit yield, incorporating structure and non-food inputs, and found that heated greenhouses in England and Germany exhibit higher energy intensity than hoop houses and open-field production in warmer climates like Israel and California (Weidner et al., 2019). A more recent LCA study on tomato greenhouse production in Austria (1.37 kg $CO_2$/kg tomato) compared with the imported supply from unheated greenhouses in Spain and Italy (0.68 kg $CO_2$/kg tomato) corroborated these findings (Theurl et al., 2014 as cited by Weidner et al., 2019). The same study highlighted the lower environmental impact of locally and organically grown tomatoes in low-yield hoop houses (0.18 kg $CO_2$/kg tomato). Another comparison between hydroponically grown lettuce in Arizona's greenhouses and conventional OF agriculture revealed the former's 11 times higher yield and 12 times less water requirement but an 82 times higher energy requirement, with heating and cooling as the primary contributors (Barbosa et al., 2015). These insights underscore the need for nuanced evaluations and considerations in understanding the infrastructural impacts of various agricultural systems (Weidner et al., 2019).

### 2.4.3 Lack of Studies in Canada

UA has witnessed significant growth globally, with leading players and influential countries including the United States, Germany, the United Kingdom, Italy, China, and Canada. This phenomenon exhibits a diverse range of forms, reflecting variations in how agricultural activities are organized and respond to market needs in each country. In Europe, encouraging food production in urban environments during the 20$^{th}$ century World Wars has led to the development of networks and research projects supporting and enhancing knowledge of urban farming. Notable examples include "The Parc des Expositions" in Paris, hosting the largest rooftop farm in Europe.

In many Canadian regions, challenging weather conditions make year-round local food production impractical, necessitating the importation of produce from other regions or countries. While initiatives and policies vary between states, there is an increasing trend of state-level involvement. According to recent research (Fresh from the City: The Rise of Urban Farming, 2021), in 2019, Canada imported $6.37 billion in fruit and $3.9 billion in vegetables, mainly from the US, China, and Mexico (Stall-Paquet, 2021). Noteworthy examples of urban farming in Canada include Lufa Farms, a rooftop greenhouse in Montreal (Quebec), and GoodLeaf Farms, a vertical farm in Guelph (Ontario). The Canadian government is actively incentivizing companies engaged in indoor farming methods, promoting water savings and GHG emission reductions. An example is Winter Farms, a Quebec-based vertical farm company, which received a $2.9 million award from Sustainable Development Technologies Canada (SDTC) for developing an artificial intelligence-based system to automate grow room controls.

Despite technological advancements in Canada, the associated energy consumption is a significant hurdle in integrating greenhouses into Northern climates' food security strategy. Cold climates require substantial supplemental heating for greenhouses during winter, posing a challenge to their widespread adoption. Addressing this challenge is crucial for Canada to fully leverage greenhouses' potential as part of a comprehensive food security strategy.

### 2.4.4 Research questions

Transportation and logistics are intricately tied to carbon emissions and energy consumption within the food supply chain. Conversely, urban farming has been posited as a potential solution to mitigate fuel consumption and reduce food waste across the supply chain. CE-UA has demonstrated remarkable efficiency in water usage compared to conventional OF practices. However, existing studies highlight a potential drawback: the increased energy consumption associated with CE-UA, raising environmental concerns.

Moreover, the inputs in CE-UA may exhibit variations compared to conventional agriculture. The use of electrical lighting and climate control in CE-UA, while it may contribute to operational energy use, has the potential to reduce input usage and enable controlled nutrient solutions and optimal environmental conditions to facilitate rapid and planned production growth. This study scrutinizes the intricate balance between these factors and aims to determine the overall sustainability of CE-UA operations. This research addresses critical questions regarding the environmental impact and sustainability of shipping container vertical farm with CEA system within Canada, shedding light on the nuanced interplay between energy consumption, input usage, and overall efficiency.

## References


Arto, I., Capellán-Pérez, I., Lago, R., Bueno, G., & Bermejo, R. (2016). The energy requirements of a developed world. Energy for Sustainable Development, 33, 1-13.

Artz, J., Müller, T. E., Thenert, K., Kleinekorte, J., Meys, R., Sternberg, A., ... & Leitner, W. (2018). Sustainable conversion of carbon dioxide: an integrated review of catalysis and life cycle assessment. Chemical reviews, 118(2), 434-504. https://doi.org/10.3389/fenrg.2020.00015

Athena Sustainable Materials Institute. (2017). LCA, LCI, LCIA, LCC: What's the difference? Retrieved from http://www.athenasmi.org/resources/about-lca/whats-the-difference/

Avgoustaki , D. D., & Xydis, G. (2020). How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety?. In Advances in food security and sustainability (Vol. 5, pp. 1-51). Elsevier. https://doi.org/10.1016/bs.af2s.2020.08.002

Barbosa. L, G., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., ... & Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. International journal of environmental research and public health, 12(6), 6879-6891.

Beacham, A. M., Vickers, L. H., & Monaghan, J. M. (2019). Vertical farming: a summary of approaches to growing skywards. The Journal of Horticultural Science and Biotechnology, 94(3), 277-283.

Benis, K., & Ferrão, P. (2017). Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA)–a life cycle assessment approach. Journal of Cleaner Production, 140, 784-795. https://doi.org/10.1016/j.jclepro.2016.05.176

Calzadilla, A., Rehdanz, K., Betts, R., Falloon, P., Wiltshire, A., & Tol, R. S. (2013). Climate change impacts on global agriculture. Climatic change, 120, 357-374. https://doi.org/10.1007/s10584-013-0822-4

Caputo, S. (2012). The purpose of urban food production in developed countries. Sustainable Food Planning, Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 259-270

Carvalho, F. P. (2006). Agriculture, pesticides, food security and food safety. Environmental science & policy, 9(7-8), 685-692. https://doi.org/10.1016/j.envsci.2006.08.002

Coley, D., Howard, M., & Winter, M. (2009). Local food, food miles and carbon emissions: A comparison of farm shop and mass distribution approaches. Food policy, 34(2), 150-155. https://doi.org/10.1016/j.foodpol.2008.11.001

Curran, M. A. (2009). Horne, R., Grant, T., & Verghese, K. (Eds.). Life cycle assessment: principles, practice, and prospects (p. 192). Csiro Publishing

Despommier, D. (2010). The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. Journal für Verbraucherschutz und Lebensmittelsicherheit, 6, 233-236.

Ekvall, T. Attributional and Consequential Life Cycle Assessment. (2019). Bastante-Ceca, M. J., Fuentes-Bargues, J. L., Hufnagel, L., Mihai, F. C., & Iatu, C. (Eds.). Sustainability Assessment at the 21st century (pp. 1-47). Intechopen. https://doi.org/10.5772/intechopen.89202

Engler, N., & Krarti, M. (2021). Review of energy efficiency in controlled environment agriculture. Renewable and Sustainable Energy Reviews, 141, 110786.

Enthoven, L., & Van den Broeck, G. (2021). Local food systems: Reviewing two decades of research. Agricultural Systems, 193, 103226.

Food and Agriculture Organization of the United Nations (FAO). (2014). The State of Food and Agriculture 2014. Innovation in family farming.

Food and Agriculture Organization of the United Nations (FAO). (2017). The future of food and agriculture: Trends and challenges. https://www.fao.org/3/i6583e/i6583e.pdf

Food and Agriculture Organization of the United Nations (FAO). (High-Level Expert Forum, 2009). How to Feed the World in 2050.

Goldstein, B., Birkved, M., Fernández, J., & Hauschild, M. (2017). Surveying the environmental footprint of urban food consumption. Journal of Industrial Ecology, 21(1), 151-165.

Goldstein, B., Birkved, M., Hauschild, M., & Fernandez, J. (2014). Urban agricultural typologies and the need to quantify their potential to reduce a city's environmental 'foodprint'. World SB14, Barcelona, 28, 24-31.

Goldstein, B., Hauschild, M., Fernández, J., & Birkved, M. (2016a). Testing the environmental performance of urban agriculture as a food supply in northern climates. Journal of Cleaner Production, 135, 984-994.

Hall, G., Rothwell, A., Grant, T., Isaacs, B., Ford, L., Dixon, J., ... & Friel, S. (2014). Potential environmental and population health impacts of local urban food systems under climate change: a life cycle analysis case study of lettuce and chicken. Agriculture & Food Security, 3(1), 1-13. https://doi.org/10.1186/2048-7010-3-6

Harris, F., Moss, C., Joy, E. J., Quinn, R., Scheelbeek, P. F., Dangour, A. D., & Green, R. (2020). The water footprint of diets: a global systematic review and meta-analysis. Advances in Nutrition, 11(2), 375-386. https://doi.org/10.1093/advances/nmz091

Hauschild, M. Z. (2017). Introduction to LCA methodology. Life cycle assessment: Theory and practice, 59-66. https://doi.org/10.1007/978-3-319-56475-3_6

Heinke, J., Lannerstad, M., Gerten, D., Havlík, P., Herrero, M., Notenbaert, A. M. O., ... & Müller, C. (2020). Water use in global livestock production—opportunities and constraints for increasing water productivity. Water Resources Research, 56(12), e2019WR026995. https://doi.org/10.1029/2019wr026995

International Institute of Sustainable Development (IISD). (2022). Generation 2030: Can Vertical Farming Stand the Test of COVID-19 and Food Insecurity?

International Organization for Standardization (ISO). (2006). Environmental management: life cycle assessment; requirements and guidelines (Vol. 14044). Geneva, Switzerland: ISO. https://doi.org/10.5555/iso14044:2006

International Organization for Standardization. (2006). ISO 14040:2006 Environmental management: life cycle assessment; Requirements and management. ISO.

IPCC. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, Eds P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, et al. (Cambridge: Cambridge University Press).

IPCC. (2021): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate. Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

J. Jones, A. (2002). An environmental assessment of food supply chains: a case study on dessert apples. Environmental management, 30, 560-576. https://doi.org/10.1007/s00267-002-2383-6

Jayasundara, P. M., & Rathnayake, M. (2023). Environmental impacts and sustainability assessment of fruit and vegetable waste valorization through life cycle assessment (includes an overview of life cycle assessment from laboratory scale to industrial implementations and social & economic sustainability). Fruit and Vegetable Waste Utilization and Sustainability, 181-212. https://doi.org/10.1016/b978-0-323-91743-8.00010-1

Jin, Q., You, J., Xie, M., Qiu, Y., Lei, S., Ding, Q., & Chen, J. (2022). Drip Irrigation Reduced Fertilizer Nitrogen Loss from Lettuce Field—A Case Study Based on 15N Tracing Technique. Water, 14(4), 675. https://doi.org/10.3390/w14040675

Karwacka, M., Ciurzyńska, A., Lenart, A., & Janowicz, M. (2020). Sustainable development in the agri-food sector in terms of the carbon footprint: A Review. Sustainability, 12(16), 6463. http://dx.doi.org/10.3390/su12166463

Knorr, D., Khoo, C. S. H., & Augustin, M. A. (2018). Food for an urban planet: challenges and research opportunities. Frontiers in Nutrition, 4, 73.

Kürklü, Ahmet & Ghafoor, Dr. Abdul & Khan, Engr. Fraz & Ali, Qasid. (2018). A Review on Hydroponic Greenhouse Cultivation for Sustainable Agriculture. International Journal of Agriculture Environment and Food Sciences, 2(2), 59-66.

Majid, M., Khan, J. N., Shah, Q. M. A., Masoodi, K. Z., Afroza, B., & Parvaze, S. (2021). Evaluation of hydroponic systems for the cultivation of Lettuce (Lactuca sativa L., var. Longifolia) and comparison with protected soil-based cultivation. Agricultural Water Management, 245, 106572. https://doi.org/10.1016/j.agwat.2020.106572

Managa, Millicent G., Peter P. Tinyani, Grany M. Senyolo, Puffy Soundy, Yasmina Sultanbawa, and Dharini Sivakumar (2018). "Impact of transportation, storage, and retail shelf conditions on lettuce quality and phytonutrients losses in the supply chain." Food science & nutrition 6, no. 6: 1527-1536. https://doi.org/10.1002/fsn3.685

Martin, M., & Molin, E. (2019). Environmental assessment of an urban vertical hydroponic farming system in Sweden. Sustainability, 11(15), 4124.

Matthews, H. S.; Hendrickson, C. T. and Matthews, D. H. (2018). Life Cycle Assessment: Quantitative Approaches for Decisions That Matter. Available: www.lcatextbook.com

McDougall, R., Kristiansen, P., & Rader, R. (2018). Small-scale urban agriculture results in high yields but requires judicious management of inputs to achieve sustainability. Proceedings of the National Academy of Sciences, 116(1), 129-134.

McManus, M. C., & Taylor, C. M. (2015). The changing nature of life cycle assessment. Biomass and bioenergy, 82, 13-26. https://doi.org/10.1016/j.biombioe.2015.04.024

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. Nature, 490(7419), 254-257. https://doi.org/10.1038/nature11420

Müller, L. J., Kätelhön, A., Bachmann, M., Zimmermann, A., Sternberg, A., & Bardow, A. (2020). A guideline for life cycle assessment of carbon capture and utilization. Frontiers in Energy Research, 8, 15.

Neeteson, J. J., Schröder, J. J., & Ten Berge, H. F. M. (2003). A multi-scale system approach to nutrient management research in the Netherlands. NJAS-Wageningen Journal of Life Sciences, 50(2), 141-151. https://doi.org/10.1016/S1573-5214(03)80003-9

Nicholson, C. F., Harbick, K., Gómez, M. I., & Mattson, N. S. (2020). An economic and environmental comparison of conventional and controlled environment agriculture (CEA) supply chains for leaf lettuce to US cities. Food Supply Chains in Cities: Modern Tools for Circularity and Sustainability, 33-68.

Nieuwlaar, E. (2004) Encyclopedia of energylife cycle assessment and energy systems. Elsevier BV, 647–654. https://doi.org/10.1016/B0-12-176480-X/00233-3.

Niewuwlaar, E., & Cleveland, C. J. (2004). Life Cycle Assessment and Energy Systems, Encyclopedia of Energy. https://doi.org/10.1016/b0-12-176480-x/00233-3

Nogeire-McRae, T., Ryan, E. P., Jablonski, B. B., Carolan, M., Arathi, H. S., Brown, C. S., ... & Schipanski, M. E. (2018). The role of urban agriculture in a secure, healthy, and sustainable food system. BioScience, 68(10), 748-759.

Opitz, I., Berges, R., Piorr, A., & Krikser, T. (2016). Contributing to food security in urban areas: differences between urban agriculture and peri-urban agriculture in the Global North. Agriculture and Human Values, 33, 341-358.

Orsini, F., Kahane, R., Nono-Womdim, R., & Gianquinto, G. (2013). Urban agriculture in the developing world: a review. Agronomy for sustainable development, 33, 695-720.

Pataki, D. E., Carreiro, M. M., Cherrier, J., Grulke, N. E., Jennings, V., Pincetl, S., ... & Zipperer, W. C. (2011). Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Frontiers in Ecology and the Environment, 9(1), 27-36.

Phelps, L. N., & Kaplan, J. O. (2017). Land use for animal production in global change studies: Defining and characterizing a framework. Global change biology, 23(11), 4457-4471. https://doi.org/10.1111/gcb.13732

PRB. (2016). 2016 World Population Data Sheet. https://www.prb.org/resources/2016-world-population-data-sheet/

R Shamshiri, R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., ... & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture.

Rajan, P., Lada, R. R., & MacDonald, M. T. (2019). Advancement in indoor vertical farming for microgreen production. American Journal of Plant Sciences, 10(08), 1397.

Schaubroeck, T. (2023). Relevance of attributional and consequential life cycle assessment for society and decision support. Frontiers in Sustainability, 4, 1063583. https://doi.org/10.3389/frsus.2023.1063583

Schröder, J. J., Scholefield, D., Cabral, F., & Hofman, G. (2004). The effects of nutrient . losses from agriculture on ground and surface water quality: the position of science in developing indicators for regulation. Environmental Science & Policy, 7(1), 15-23. https://doi.org/10.1016/j.envsci.2003.10.006

Sihvonen, M., Pihlainen, S., Lai, T. Y., Salo, T., & Hyytiäinen, K. (2021). Crop production, water pollution, or climate change mitigation—Which drives socially optimal fertilization management most?. Agricultural Systems, 186, 102985.

Stein, E. W. (2021). The transformative environmental effects large-scale indoor farming may have on air, water, and soil. Air, Soil and Water Research, 14, 1178622121995819.

Tapia, C., Randall, L., Wang, S., & Borges, L. A. (2021). Monitoring the contribution of urban agriculture to urban sustainability: an indicator-based framework. Sustainable Cities and Society, 74, 103130.

Taylor, M. D., Klaine, S. J., Carvalho, F. P., Barcelo, D., & Everaarts, J. (Eds.). (2003). Pesticide residues in coastal tropical ecosystems: distribution, fate and effects. CRC Press. https://doi.org/10.1201/9780203165584

Theurl, M. C., Haberl, H., Erb, K. H., & Lindenthal, T. (2014). Contrasted greenhouse gas emissions from local versus long-range tomato production. Agronomy for sustainable development, 34, 593-602. https://doi.org/10.1007/s13593-013-0171-8

Tilman, D., Fargione, J., Wolff, B., D'antonio, C., Dobson, A., Howarth, R., ... & Swackhamer, D. (2001). Forecasting agriculturally driven global environmental change. science, 292(5515), 281-284. https://doi.org/10.1126/science.1057544

Touliatos, D., Dodd, I. C., & McAinsh, M. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food and energy security, 5(3), 184-191.

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., ... & Wernet, G. (2013). Overview and methodology: Data quality guideline for the ecoinvent database version 3. www.econivent.com

Weidner, T., Yang, A., & Hamm, M. W. (2019). Consolidating the current knowledge on urban agriculture in productive urban food systems: Learnings, gaps and outlook. Journal of Cleaner Production, 209, 1637-1655.

Yan, D., Liu, L., Liu, X., & Zhang, M. (2022). Global trends in urban agriculture research: A pathway toward urban resilience and sustainability. Land, 11(1), 117. http://dx.doi.org/10.3390/land11010117

York University. (n.d.). Food Policy of Canada. Sustainable transportation: Challenges of food transport in Canada. https://foodpolicyforcanada.info.yorku.ca/goals/goal-5/sustainable-transportation/challenges-transport/#:~:text=With%20Canada's%20reliance%20on%20trucked,range%20(Klein%2C%201987).

Zabel, F., Delzeit, R., Schneider, J. M., Seppelt, R., Mauser, W., & Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nature communications, 10(1), 2844. https://doi.org/10.1038/s41467-019-10775-z

Zaręba, A., Krzemińska, A., & Kozik, R. (2021). Urban vertical farming as an example of nature-based solutions supporting a healthy society living in the urban environment. Resources, 10(11), 109.

Zhang, H., Asutosh, A., & Hu, W. (2018). Implementing vertical farming at university scale to promote sustainable communities: a feasibility analysis. Sustainability, 10(12), 4429.

Zhang, X., & Cai, X. (2011). Climate change impacts on global agricultural land availability. Environmental Research Letters, 6(1), 014014. https://doi.org/10.1088/1748-9326/6/1/014014

Zhong, Q., Wang, L., & Cui, S. (2021). Urban food systems: A bibliometric review from 1991 to 2020. Foods, 10(3), 662.

## Connecting Text to Chapter 3

**Chapter 2**, literature review, served as the foundation for the research conducted in Chapter 3, which focuses on comparing the environmental impacts of Controlled Environmental Urban Agriculture (CE-UA) to Open-Field (OF) conventional agriculture in Canada for 1 kg of delivered lettuce. It explores various aspects such as global food system challenges, urban agriculture, CE-UA, and life cycle assessment LCA, providing background knowledge and a theoretical framework for understanding the environmental implications of different agricultural methods.

**Chapter 3**, manuscript, develops the research methodology based on insights from the literature review, tailoring LCA methodology to evaluate the sustainability of CE-UA operations and quantify the environmental impacts across different provinces and climates in Canada. It considers factors like GHG emissions, LU, and WRD, which are crucial for assessing the environmental footprint of agricultural practices. The results, derived from empirical data collected through site visits, are analyzed within the conceptual framework established in the literature review, providing insights into the comparative environmental performance of CE-UA and conventional agriculture. This chapter has been submitted for peer review in the journal *Agronomy for Sustainable Development* with Estefany Cabanillas as the lead author in March 2024. The chapter format aligns with the thesis requirements, and all relevant literature is appropriately referenced.

# Chapter 3: Manuscript

## Comparing high-tech urban agriculture to conventional agriculture in Canada

Estefany Cabanillas, Dr. Benjamin Goldstein, Dr. Mark Lefsrud

### Abstract

The growth and increasing urbanization of the world's population necessitates re-evaluating how cities procure food. Urban food systems rely heavily on industrialized agriculture that imparts significant environmental impacts and extended supply chains that produce food waste. Controlled-environment urban agriculture (CE-UA) is argued to make urban food systems more sustainable and resilient by shortening supply chains and producing food efficiently in indoors. This study explores the environmental impacts of CE-UA through a case study of high-tech urban lettuce farming in Canada. We find that CE-UA provides some environmental benefits, such as reduced (or comparable) water use and land use relative to conventional agriculture. Climate change impacts, however, vary from 0.8 to 25 times those of conventional lettuce because of the high energy demands of CE-UA. In areas of Canada with carbon-intensive energy grids, such as Alberta, CE-UA has much higher carbon emissions per kilogram lettuce than conventional lettuce. In contrast, areas using renewables, like Quebec, have comparable emissions to market-average lettuce or much lower emissions than Canadian greenhouses. This suggests that CE-UA in Canada and other cold climates is not automatically low-carbon but can be if low-carbon energy sources are available. As such, CE-UA should be deployed in cities with existing low-carbon energy grids or in conjunction with nearby low-carbon energy sources to

realize its potential to provide local fresh produce and contribute to low-carbon urban food systems.

## 3.1 Introduction

As cities continue to grow, it is increasingly necessary to rethink how and where food is produced for cities. Food production faces obstacles such as competition for land, water scarcity, extreme weather conditions, and environmental pollution, which have all impacted food security and compromised food system sustainability. At the same time, global food production is a primary driver of global biodiversity loss, nutrient loss, soil pollution and erosion, land use change, and water use (Poore & Nemecek, 2018; Ritchie & Roser, 2022; Alexander et al., 2017), as well as the source of over 26% of the global anthropogenic greenhouse gas (GHG) emissions (Ritchie & Roser, 2022).

Agricultural production is decidedly rural, and affluent cities often source food from lengthy global supply chains— this distance from farm to fork results in significant food waste and additional GHG emissions from transport. Long and complex webs of supply chains are susceptible to disruptions (e.g., COVID-19). Moreover, the time gap between harvest and consumption can lead to a substantial loss of nutritional value (i.e., nutrient content) from storage, ranging from 30% to 50% (York University, n.d.). Urban agriculture (UA) bypasses these supply chains by growing food in and around cities. UA comes in many forms, from low-tech community gardens to high-tech controlled-environment agriculture (CEA), such as urban greenhouses, container farms, and vertical farms (Hawes et al., 2024; Goldstein et al., 2016b).

There is growing interest in controlled-environment-urban agriculture (CE-UA), given its potential to efficiently grow large amounts of food using little space (Kozai et al., 2019).

CE-UA can improve yields and curb water and nutrient use by tailoring growing conditions and eliminating dissipative losses. For example, CE-UA can achieve remarkable water savings, up to 70-95% compared to conventional open field (OF) farming practices (Barbosa et al., 2015). Moreover, exhibiting remarkable crop yields, with an average of 6.88 $kg/m^2$, surpassing the global average of 3.68 $kg/m^2$ and the FAO field results of 1.88 $kg/m^2$ (Gargaro et al., 2023). Moreover, through the optimization of fertilizer application, while not completely eliminating such risks, these systems significantly reduce them. This underscores their efficacy in enhancing food safety and optimizing resource allocation (Cowan et al., 2022; Vatistas et al., 2022).

By using electric lighting and external heat sources, CE-UA can be deployed in areas with little sunlight, cold climates, and other challenging growing conditions, improving access to fresh foods and strengthening food security in remote areas, cities in cold climates, or underserved urban territories (Kozai et al., 2019). Despite producing high yields and minimizing water and fertilizer use, CE-UA often uses large amounts of energy, translating into significant GHG emissions when energy comes from fossil sources.

Studies suggest higher environmental impacts associated with CE-UA compared to conventional agriculture. For instance, a study conducted in The Netherlands for lettuce revealed that the carbon footprint of CE-UA was considerably higher than that of conventional farming methods. In the baseline scenario, the carbon footprint of the CE-UA farm was 5.6 to 16.7 times greater than conventional farming methods, and in an alternative scenario, using renewable energies, it was 2.3 to 3.3 times higher (Blom et al., 2022). Another study highlighted that while hydroponic systems reduce water usage by 13 times, their reliance on electrical lighting and climate control can increase GHG emissions. In addition, CE-UA can yield 11 times more lettuce but requires 82 times more energy compared to conventional methods. The primary contributors to this energy consumption are heating and cooling systems, which account for 82% of the total energy usage, and lighting contributes 17% (Barbosa, et al., 2015).

Although studies of CE-UA are multiplying, knowledge gaps remain about the trade-offs between high yield, resource efficiency, and GHGs in CE-UA. Given the dependence of results on the carbon intensity of the energy grid and focus of studies on a single location, it remains unclear how CE-UA performs across large countries where energy grids vary significantly. This challenges the generalizability and applicability of findings across diverse scenarios. Moreover, studies have often only considered how CE-UA compares to the “average” crop available year-round in a city, even though variations in sourcing strategies throughout the year (e.g., open-field in summer, greenhouse in winter) can influence study conclusions. For instance, Plawecki et al. (2014) showed that GHG intensity of locally-sourced open-field lettuce in Michigan, United States could be 4.3 times lower than winter lettuce shipped from California. Such variations could influence the environmental preferability of CE-UA.

This study addresses these gaps through a study of CE-UA across Canada. Canada is an interesting case study of CE-UA for several reasons. Labor shortages persist across Canada’s agricultural landscape, with the greenhouse industry notably struggling to fill positions, contributing significantly to industry-wide workforce gaps. The vulnerability of this sector to labor shocks was starkly evident during the COVID-19 pandemic, underscoring the urgent need for innovative solutions to enhance productivity and reduce reliance on manual labor. Projections from the Canadian Agricultural Human Resource Council suggest an impending increase in global demand for Canadian agricultural products, necessitating production levels and workforce efficiency adaptations. At the same time, Canada imports significant amounts of fresh produce at various times of the year. Moreover, Canada is a cold, large country, making it an ideal context to study the environmental performance of CE-UA in challenging conditions using fossil and low-carbon energy.

Here, we use life cycle assessment (LCA) to assess the environmental performance of lettuce grown in a novel CE-UA system comprised of an array of shipping containers operating in a large warehouse in Montreal (MTL). Primary data on energy consumption, water usage, yields, fertilizer, and waste were collected and used to calculate life cycle impacts across three indicators relevant to agriculture: Global Warming Potential (GWP), Land Use (LU), and Water Resource Depletion (WRD). GWP is an indicator of potential global warming due to emissions of GHG into the air. This metric evaluates the Climate Change impacts expressed as kg $CO_2$-eq. The LU indicator accounts for agricultural land expansion and degradation, providing insights into the changes in land use patterns driven by agriculture. Additionally, WRD, an indicator of the relative amount of water consumed, based on regionalized water scarcity factors measuring the remaining water availability within a watershed after fulfilling the needs of both human consumption and aquatic ecosystems, evaluating the water use (WU) impacts expressed in m3 world eq (Jayasundara & Rathnayake, 2023).

These were then compared to OF lettuce production in California (the primary source during winter), local OF, local greenhouse (GH) production, and market average lettuce. Through scenario analysis, we evaluated the potential environmental performance of the CE-UA system in all of Canada's 13 provinces and territories. The following sections outline the case study CE-UA system, describe the LCA methods and data for lettuce produced using CE-UA and conventionally, provide an overview of our scenarios, and present results and discussion. Our results suggest that CE-UA can produce local, fresh food with comparable or lower environmental impacts than conventional sources in some areas of Canada or during specific seasons. However, its high energy use means it should be implemented alongside on-site low-carbon sources in some provinces to maximize these benefits.

## 3.2 Methods

Life Cycle Assessment (LCA), standardized by ISO protocols, evaluates environmental impacts across all stages of product systems, from raw material extraction to disposal. It quantifies contributions to global warming and other significant environmental footprints like carbon, water, land, and energy (McManus & Taylor, 2015). Matthews et al. (2018) discuss two LCA approaches: cradle-to-gate focuses on impacts from extraction to manufacturing, while cradle-to-grave assesses the entire lifecycle, including disposal or recycling. LCA (ISO 14044:2006) aids decisions on environmental sustainability for products, processes, and services, comparing overall impacts. For this study, we use LCA to study CE-UA in Montreal, Canada, and conventional lettuce available on the Canadian market.

### 3.2.1 Modelling Framework

LCA is a systematic approach to evaluating environmental impacts across all stages of a product's life, from raw material extraction to disposal or recycling. Despite international standards (ISO 14040 and ISO 14044), LCA studies vary in implementation due to differences in boundaries, data inputs, computational methods, and results (Nicholson et al., 2020). Figure 3.1 illustrates the phases of an LCA: Goal and Scope definition, Life Cycle Inventory analysis, Life Cycle Impact Assessment, and Interpretation (Rebitzer et al., 2004).

The depth and breadth of an LCA depend on its objectives, with the Life Cycle Inventory (LCI) analysis phase compiling data essential to the study's goals. The subsequent Life Cycle Impact Assessment (LCIA) phase provides insights into the environmental significance of the LCI results, while the Interpretation phase synthesizes outcomes for decision-making (ISO 14044:2006). ALCA assesses current environmental impacts, focusing on direct consequences and resource use, while CLCA considers broader systemic impacts and potential changes in a system (Schaubroeck, 2023; Weidema et al., 2013).

We employ a process-based LCA approach that utilizes comprehensive data covering the entire life cycle, including specific processes such as fertilizer application and distribution. We utilized ALCA, modeling historical providers in the product life cycle, aligned with ISO recommendations (ISO, 2006), and integrated with the ecoinvent 3.8 database (Ecoinvent Database, 2023) with the OpenLCA (www.openlca.org) product system modeling software.

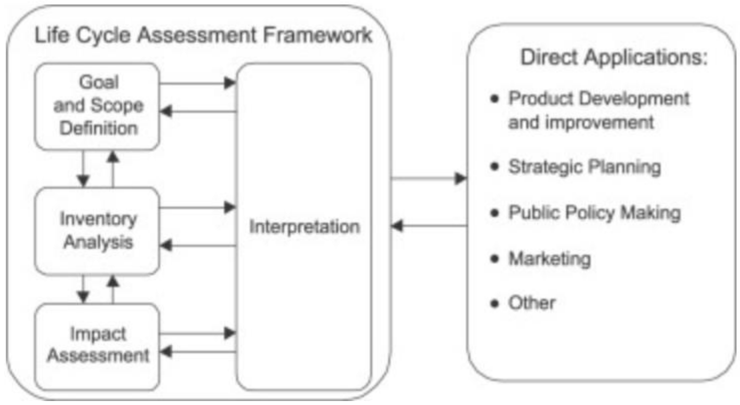



**Figure 3.1:** Phases and applications of an LCA, based on ISO 14040 (Rebitzer, et al., 2004)

### 3.2.2 System Boundaries and Functional Unit

The objective and scope of our study define the product system's boundaries and establish a functional unit (FU), essential for meaningful comparisons (Rebitzer et al., 2004; Müller, 2020). Our scope is cradle-to-gate, which includes farming and any distribution to the point sale. There are no processing steps in our product system. Figure 3.2 illustrates the system boundaries included in this assessment. Although the infrastructure was included for the CE-UA systems that these farms' operations consist mainly of the hydroponic system infrastructure, we have chosen not to include the building infrastructure for the conventional systems as this does not have marginal impacts on results in other LCAs of lettuce and usually not included to the inconsistency on studies comparison.

Studies highlight the significance of infrastructure in influencing various environmental impact categories. However, it is essential to acknowledge that these findings are sensitive to underlying assumptions and methodological choices, which can serve as limitations. For instance, Martin et al. (2023) exposed that the infrastructure assumptions in conventional farming regarding the lifespan of different structures and machinery can significantly impact the overall system impact. Additionally, since the CE-UA is located within a repurposed warehouse facility, the building infrastructure (envelope) was not included in the assessment. While the operational shipping container infrastructure components were considered, this envelope omission may underestimate the environmental implications, especially considering the potential impact of building renovations.

Nonetheless, past research indicates that building energy usage and other operational impacts typically overshadow the environmental effects of the building envelope itself (Fnais et al., 2022). Moreover, repurposing existing buildings and infrastructure can offer regional development and sustainability benefits while preserving heritage, as demonstrated in previous studies (Chance et al., 2018; Dell'Anna, 2022; Foster, 2020, as cited by Martin et al., 2023). However, such benefits were not explored in this study.

Moreover, studies show packaging is crucial in waste handling, particularly in end-of-life scenarios. However, its contribution to overall system impacts and per FU is minimal. (Martin et al., 2023). Therefore, the end-of-life was not included due to this small contribution and because it is assumed to be the same for both the CE-UA and conventional systems. Since the end-of-life was not included and challenges in cross-system comparisons, we opted to exclude packaging from conventional farming and CE-UA analysis to ensure methodological consistency in our modeling approach. This decision underscores the sensitivity of the analysis to methodological considerations.

In this assessment, we have chosen one kg of fresh lettuce as the FU available for consumption in Montreal, QC. Lettuce is the primary crop produced by our industrial partners. We chose lettuce because it is one of Canada's most common and popular fresh produce crops. Based on Statistics Canada (2023), in Canada, the total (produced + import-export) lettuce available in the market for consumption is 323,934 tonnes annually, with about 6-7% of the total being lost in the supply chain from production to destination, of which 15% coming from the transportation portion. Per year, 8.32 kg of lettuce is available for consumption per person in Canada.

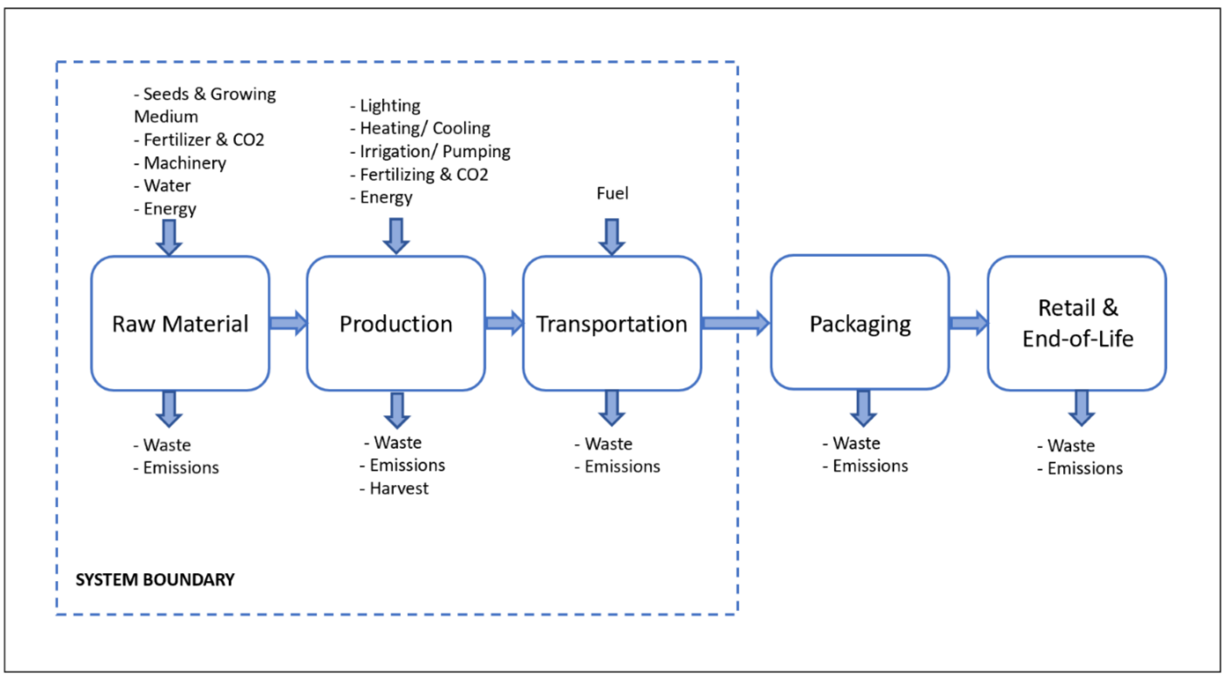



**Figure 3.2:** Activities included in the system boundaries

### 3.2.3 Case Studies and life-cycle inventory

In the realm of LCA, an inventory, often referred to as Life Cycle Inventory (LCI), involves a comprehensive analysis of materials and energy throughout the examined system's life cycle, from creation to disposal (Klöpffer & Grahl, 2014). This phase, according to ISO standards, involves compiling and quantifying inputs and outputs across the product's entire life cycle. It requires gathering diverse environmental data and quantifying elements such as energy and raw material requirements, emissions, and waste (Curran, 2009).

This study focuses on two farming systems: CE-UA and conventional production using OF and GH. We analyzed one CE-UA operation in Montreal (CE-UA-MTL), Canada. The CE-UA system consists of a single shipping container farm in a warehouse. This is a prototype of a system that will eventually have an array of a dozen or more farms producing lettuce year-round in a single warehouse. The conventional systems were modeled using existing LCAs. We grouped the life cycle inventory (LCI) into three categories: farm infrastructure, supplies, and transportation. Table 3.1 outlines the specific components of the product systems that fall under the three main categories.

**Table 3.1:** Process grouping for the analysis included in the system boundaries

| | Open Field | Greenhouse | Canadian Market | CEA |
|---|---|---|---|---|
| **Processes** | Supplies<br>Transportation | Supplies<br>Transportation | Supplies<br>Transportation | Supplies<br>Infrastructure<br>Transportation |

#### 3.2.3.1 Conventional Open Field (OF) and Greenhouse (GH) Systems

OF is cultivating crops in soil exposed to the air by applying nutrients, pesticides, and herbicides. It often relies on rainfall and is sometimes supplemented with additional irrigation (Barbosa et al., 2015). For profitability, it requires the use of machinery such as tractors, storage facilities, and extensive land (Blom et al., 2022).

We include the sourcing of lettuce from conventional production methods with different origins based on previous research and statistics on lettuce imports. California produces the vast majority of lettuce during the winter months. The LCI for California OF was taken from UC Irvine crop budgets (Tourte et al., 2017) to reflect the imported scenario of the Canadian Market. In the summer, Canadian-produced lettuce, which is assumed to be produced using GH and OF methods, is available in the conventional supply chain. According to Statistics Canada (2023), the Canadian market lettuce consists of 33% produced domestically, of which 85% is produced in the greenhouse (15% from OF production in Quebec), and 67% is imported, mainly from California. Due to a lack of inventory data from OFs produced domestically in Canada, we assumed that domestically, lettuce production follows practices akin to OF's in the United Kingdom and The Netherlands, with conditions resembling those in Canada. For this OF domestic farm systems, we have used lettuce production inventory data in The Netherlands taken from Blom et al. (2022). For the United Kingdom, the inventory data was taken from research by Canals et al. (2008). For the OF and CE-UA systems, the inventory was taken from the mentioned studies and site visits for the CE-UA scenario, and the LCA was built in OpenLCA using the Ecoinvent v.3.8 database. In the case of domestic GH scenarios, we have utilized the

LCI system from an existing process in the Ecoinvent v. 3.8 database but made geographical and energy changes to reflect Quebec's conditions.

All background processes in the OF LCAs are changed to reflect Canadian production conditions (irrigation, energy use). The LCI for OF and GH lettuce production scenarios is available in Appendix A.1. This inventory comprehensively covers various vital processes:

**Supplies:** This category accounts for essential production supplies, including seeds, nutrients, water, land usage, and electricity consumption. These inputs are vital to the successful cultivation of lettuce within open-field farming systems.

**Transportation:** This study examined transportation distances for lettuce using cooling reefer trucks. Imported lettuce from Salinas Valley, California, to Canada covered distances of 4896 km to Montreal, 1667 km to Vancouver, and 2315 km to Alberta. For domestic scenarios, lettuce traveled an average of 200 km (Canals et al., 2008). The study models transportation emissions per kilogram of lettuce based on "t*km lettuce" for each configuration.

#### *3.2.3.2 CE-UA in Montreal*

The baseline scenario in this research, CEA-UA-MTL, is based on the resource and energy consumption data collected during one year of production at a CE-UA industrial facility for the 2022 growing season. This includes all infrastructure, material inputs, production outputs, waste, transportation, water, and energy consumption. An overview of the production of 1 kg of lettuce material inputs and outputs of the system and further details on the assumptions and modeling employed in the CE-UA-MTL scenario is available in Appendix A.2. The electricity mix for CE-UA-MTL consists of hydro (94 %), wind (5 %), biomass (0.7 %), and fossil fuel (less than 1 %). The processes were chosen from ecoinvent 3.8. database and the electricity mix assumptions taken from Provincial and Territorial Energy Profiles (Canada Energy Regulator, 2024), found in Appendix A.3. Overall, the plant expects to have 13 shipping containers for plant production. One shipping container produces 4140 heads of lettuce per cycle, with 13 cycles per year. The LCI for CE-UA lettuce production is detailed below, covering essential processes:

**Supplies:** Similar to conventional methods, this category encompasses vital resources required for production, including seeds, nutrients, water, land utilization, electricity usage for lighting, carbon dioxide enrichment, and heating, ventilation, and air conditioning (HVAC). Electricity usage is recorded for the entire farm, which precludes individual end-use analysis. These inputs are crucial for cultivating lettuce in open-field farming systems.

**Infrastructure:** Consists of all the material inputs for the seedling production, hydroponic system, and shipping container. We do not include the impacts of the industrial building that house the array of container farms as it is decades old and underwent no modification to house the containers. Also, note that the infrastructure shared between the 13 containers is divided by 13 to allocate to the lettuce produced by one container. Details on the sub-process for infrastructure are as follows:

- **Seedling:** In contrast to conventional methods, the irrigation process is divided into two distinct categories: seedling and hydroponics. The seedling stage accounts for the germination phase, encompassing all inputs involved in this process and the necessary equipment, such as fans, heating, cooling, and sensors.

- **Hydroponics:** This process covers all aspects of pumping and the irrigation system during the plant's growth stage, from the seedling phase until they are ready for harvest. It includes various components such as fans, heating, cooling, sensors, pumps, osmosis systems, and racks.

- **Shipping Container:** This process involves all the materials related to the container, including hoses, the control center, wires, and other associated components.

**Transportation:** This study examined transportation distances for lettuce using cooling reefer trucks. CE-UA lettuce travels an average of 200 km (Canals et al., 2008). The study models transportation emissions per kilogram of lettuce based on "t*km lettuce" for each configuration.

This LCI framework provides a comprehensive overview of the inputs, processes, and outputs in CE-UA shipping container lettuce production, which is crucial for evaluating its environmental impact and sustainability.

#### *3.2.3.3 Scenarios of CE-UA Across Canada*

These CE-UA models were developed to reveal the outcomes of the same farm under varying weather conditions and with access to different provincial or local resources, particularly energy sources. The objective was to assess whether the farm's location significantly influenced the results, allowing for a deeper understanding of the impact of geographical and climatic factors on carbon emissions and air quality. We modeled the Montreal-based CE-UA-MTL system across Canada, adjusting the energy grid to align with each province's specific energy infrastructure. Given that the domestic average distance was assumed to remain consistent across all scenarios and its impact on the results was marginal, transportation was excluded from the final results in Figure 3.4, providing a more precise depiction of the farms' emissions operations across various Canadian locations.

### 3.2.4 Impact Categories

LCA impact categories denote the environmental aspects or domains scrutinized to comprehend the potential environmental implications of a product, process, or service across its life cycle (ISO 14044, 2006). The selection of impact categories is crucial for conducting a holistic environmental assessment and avoiding the displacement of environmental burdens (Mikosch, 2022). During this phase, the environmental loads identified in the inventory analysis are categorized into areas such as climate change, ozone depletion, acidification, toxicological stress on human health and ecosystems, eutrophication, resource depletion, land use, water use, and additional factors (Jacquemin et al., 2012).

We assess three impact categories in our LCA: global warming potential (GWP), land use (LU), and water resource depletion (WRD). We use the ReCiPe 2016 midpoint life cycle impact assessment methodology for GWP and land use. We opted for ReCiPe over TRACI due to its inclusion of the land use category, which TRACI lacks, despite their high correlation for climate change indicators (Dong et al., 2021). ReCiPe supports three perspectives: individualist (short-term, tech optimism regarding environmental change), egalitarian (long-term thinking using precautionary principle), and hierarchies (middle ground between the other perspectives). We use the hierarchist perspective in this LCA as it is a consensus model in line with other scientific models.

GWP is utilized to evaluate the global warming impacts of different gases, measured as kg $CO_2$ equivalent per kg of lettuce (kg $CO_2$ eq./ FU) over a specific time interval. LU is assessed in $m^2a$ crop eq equivalent per FU ($m^2a$ crop eq/FU), indicating species loss relative to specific land use types such as annual crops, permanent crops, mosaic agriculture, forestry, urban land, and pasture (Huijbregts et al., 2017). LU also accounts for agricultural land expansion and degradation, reflecting changes in land use patterns driven by agriculture. In addition, to assess WRD, we employ the AWARE (Available Water Remaining) method, accounting for water availability/scarcity footprint and measured as $m^3$ equivalent per FU ($m^3$eq/FU), to consider spatial heterogeneity in water availability across production geographies (Lee et al., 2019; Ansorge & Beránková, 2017). This approach evaluates water scarcity footprint based on water consumption and AWARE-annual characterization factor (CF) data provided by Boulay et al., 2018, sourced from WULCA, specifically, data from the Canadian region are used for domestic production, while data from the United States are applied for the imported portion of the Canadian market. WRD calculations can be found in Appendix A.4

## 3.3 Results

Our study examines the environmental impacts of lettuce produced using OF, GH, and CE-UA for Canadian urban markets. We find that the environmental performance of CE-UA varies significantly by indicator and location. For WRD and LU, CE-UA performs on par or better than Canadian Market, regardless of production location. GWP shows much more variation in performance because of the influence of the energy grid. Below, we present our results for each indicator in detail and highlight environmentally intensive processes in lettuce production to inform discussions about how to make CE-UA more sustainable.

### 3.3.1 Global Warming Potential (GWP)

Figure 3.3 shows GWP results for individual sources of conventional lettuce, Canadian market average lettuce (a weighted average of OF in California, domestic OF, and GH in Quebec), and CE-UA in Montreal (MTL), Alberta (AB), and British Columbia (BC). The GWP of CE-UA-MTL is 0.64 kg $CO_2$-equivalents per FU (kg $CO_2$e/FU), which is similar to the Canadian market average (0.65 kg $CO_2$e/FU), and both imported (0.50 kg $CO_2$e/FU) and domestic OF (0.61 kg $CO_2$e/FU) production. OF and Canadian Market results are within the expected range of other studies of conventional production. For instance, an OF farm growing lettuce in Boston, where natural gas is the main energy source for electricity, had a GWP of around 0.92 kg $CO_2$e/kg (Goldstein et al., 2016a). GWP results of CE-UA-MTL are significantly lower than conventional GHs (2.9 kg $CO_2$e/FU). This suggests that CE-UA can be a year-round solution for fresh produce without exacerbating the city's GHG footprint and should even be promoted to supplant GH lettuce supplies. However, GWP results of CE-UA vary significantly by location. CE-UA-BC emits 2.0 kg $CO_2$e/FU and CE-UA-AB emits 12 kg $CO_2$e/FU. So, although CE-UA can sometimes match the GWP performance of market lettuce, it can also exceed it by factors ranging from 2 to 18. A deeper look into the processes driving GWP results reveals this.

The primary contributors to the GWP of domestic OF lettuce production stem from on-farm diesel (48%) use and nutrients and compost (47%). Transportation from California to Montreal drives 77% of the GWP impact for OF imports. On-farm emissions for this system (0.49 kg $CO_2$e/FU) are smaller than for domestic production. Conversely, CE-UA is primarily driven by substantial energy inputs needed to maintain ideal indoor growing conditions, encompassing heating, cooling, and humidity regulation. In CE-UA scenarios, the primary contributors to infrastructure hydroponic systems include the container structure (24%), HVAC system (12%), osmosis system (11%), and LED lighting (9%). When high energy use is combined with fossil fuel-dominated electrical grids, such as in AB, the GWP of CE-UA-AB can be up to 18 times higher than conventional alternatives. Notably, where the grid relies on low-carbon primary energy sources, such as in CE-UA-MTL, where 94% of electricity is from hydropower (C.E.R., 2024), farm infrastructure contributes as much to GWP as energy use.

Delving deeper into the breakdown of GWP results by processes, as shown in Table 3.2, we find that in OF methods, significant contributions stem from the direct material inputs such as diesel, nutrients, and compost, aligning with findings from other studies (Barbosa et al., 2015; Martin et al., 2023; Jensen et al., 2024). While the main driver for the OF-import method is supplies, the OF-Domestic method may require more nutrients. In colder climates like Montreal, there is less time for nutrient cycling and replenishment in the soil. Moreover, extreme temperature fluctuations common in colder climates can lead to soil erosion and nutrient leaching, further depleting soil fertility. Energy consumption remains a primary influence in GH production, especially since most comes from a mix of on-site fuel oil, natural gas, propane, and wood pellets (IRDA, 2017).

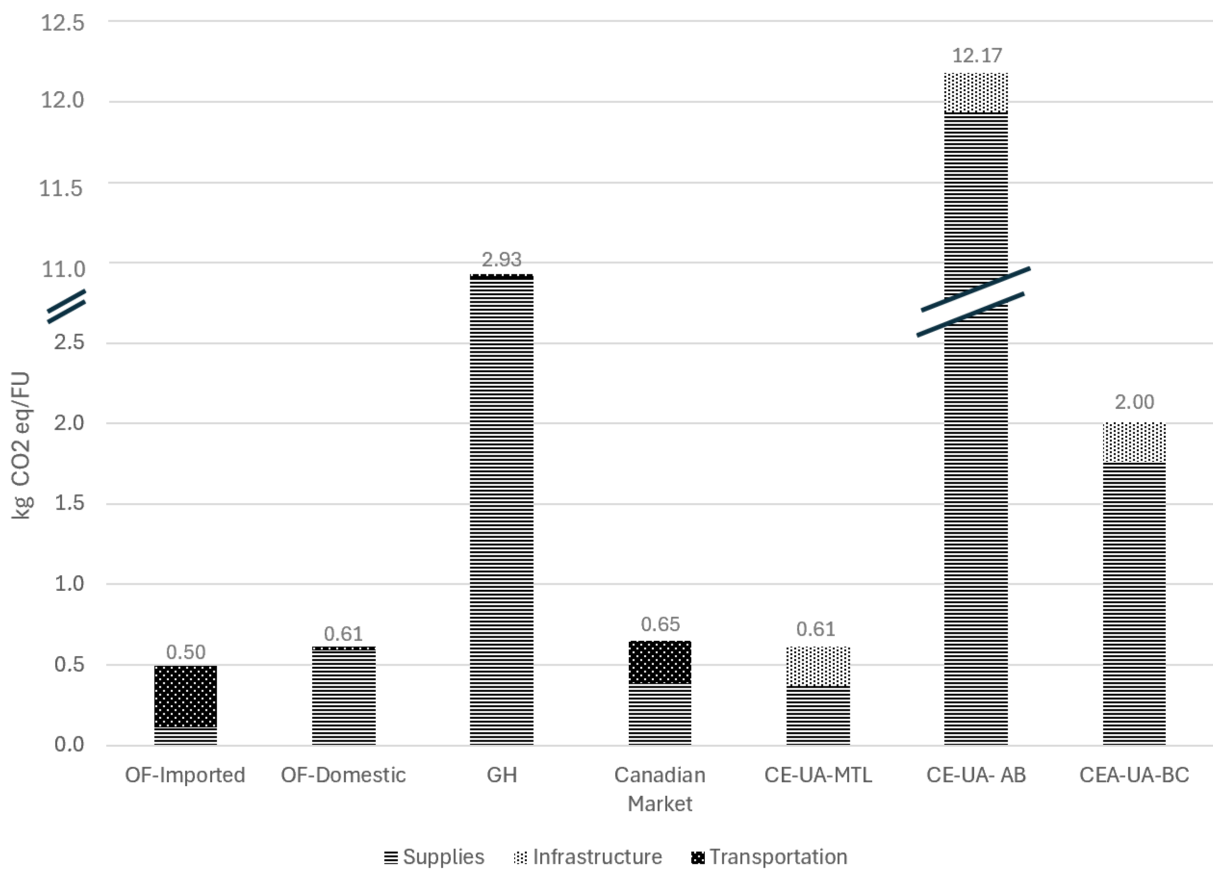



**Figure 3.3:** GWP of Conventional (imported, domestic), greenhouse (domestic), Canadian Market and CE-UA-MTL lettuce

**Table 3.2:** Breakdown of GWP impacts by category and key drivers. Disagreements between the middle and right columns are from rounding.

| Farm System | Contribution by category | Key Drivers |
|---|---|---|
| **OF-Import** | 22.82% Supplies<br>77.17% Transportation | *compost 11%, nutrients 6%, energy 5%, water 1%*<br>*transport 77%* |
| **OF-Domestic** | 95.92% Supplies<br>4.07% Transportation | *energy 48%, nutrients 46%, compost 1%, water 1*<br>*transportation 4%* |
| **GH** | 99.14% Supplies<br>0.85% Transportation | *energy 98%, compost 1%, nutrients 1%*<br>*transport 1%* |
| **Canadian Market** | 59.51% Supplies<br>40.48% Transportation | *energy 21%, compost 19%, nutrients 18%, water 1%, seeds 1%*<br>*transport 40%* |
| **CE-UA-MTL** | 57.92% Supplies<br>38.14% Infrastructure<br>3.92% Transportation | *energy 57%*<br>*hydroponic 31%, seedling 7%*<br>*transport 4%* |
| **CE-UA-AB** | 97.78% Supplies<br>2% Infrastructure<br>0.20% Transportation | *energy 98%*<br>*hydroponic 2%*<br>*transport 0.2%* |
| **CE-UA-BC** | 86.75% Supplies<br>12% Infrastructure<br>1.24% Transportation | *energy 87%*<br>*hydroponic 10%, seedling 2%*<br>*transport 1%* |

*** OF, GH, and Canadian Market supplies include: energy, nutrients, water, seeds, and land use*

*** CE-UA supplies include: energy, water, and nutrients*

*** CE-UA Infrastructure include: container infrastructure, hydroponic system, and seedling room*

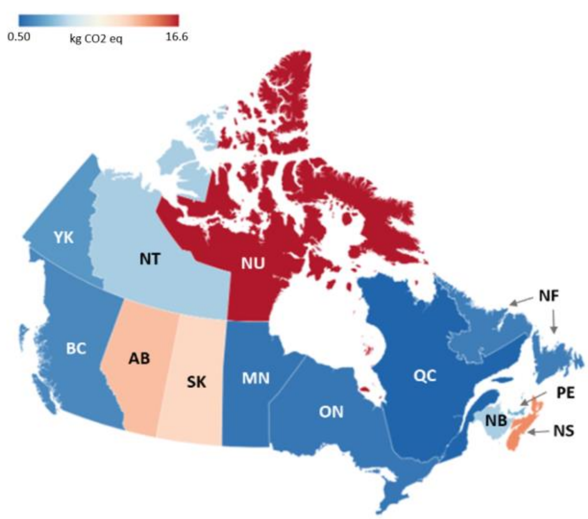
#### *3.3.1.1 GWP of CEA Across Canada*

Figure 3.4 displays the results of our scenario analysis of GWP across all 13 Canadian provinces and territories, highlighting where CE-UA should be implemented to maximize climate mitigation benefits. In addition to Quebec, CE-UA in Prince Edward Island has a similar GWP performance to Canadian market lettuce (0.52 kg $CO_2$e/FU). GWP results for CE-UA are higher than the Canadian market average in Ontario (1.3 g $CO_2$e/FU), Manitoba (1.0 kg $CO_2$e/FU), Newfoundland & Labrador (1.6 kg $CO_2$e/FU), and Yukon (2.6 kg $CO_2$e/FU), but remain lower than GH production. As expected, these provinces predominantly use low-carbon sources in their electrical grid. In provinces still reliant on fossil fuels for electricity, the GWP of CE-UA can be markedly higher than conventional alternatives: Northwest Territories (4.9 kg $CO_2$e/FU), New Brunswick (4.9 kg $CO_2$e/FU), Saskatchewan (11 kg $CO_2$e/FU), Nova Scotia (14 kg $CO_2$e/FU), and Nunavut (17 kg $CO_2$e/FU).

All these results are within the expected range of other CE-UA studies. For instance, container farms growing lettuce in Boston, where hydro and wind are the primary energy sources for electricity, had a GWP of around 0.79 kg $CO_2$e/kg (Martin et al., 2023). In another study of CE-UA in the Netherlands growing butterhead lettuce, Blom et al. (2022) estimated 8.2 kg $CO_2$e/kg with mainly fossil fuel electricity sources and 1.2 kg $CO_2$e/kg for the renewable energy alternative scenario.

As such, the results of this and other studies suggest that localizing agriculture using CE-UA is not automatically low-carbon. Although localization reduces food miles, the CE-UA requires substantial energy. Sourcing this energy from fossil fuels has unintended climate impacts. However, deploying CE-UA strategically where electricity is low-carbon or supplants GHs provides clear climate benefits to cities.

Even if CE-UA is carbon intensive in some jurisdictions, it can be essential in providing fresh vegetables to northern territories and communities grappling with food insecurity and extremely high grocery prices (Government of Canada, 2015). The issue of food insecurity is particularly acute in Canada's northern regions compared to other parts of the country. Household food insecurity rates are alarmingly high, reaching 17%, 22%, and 57% in the Yukon, the Northwest Territories, and Nunavut, respectively (Leblanc-Laurendeau, 2020). Notably, many arctic and sub-arctic communities heavily rely on air transportation for fresh produce, especially those lacking year-round surface transportation options. These communities are typically situated in remote regions of Canada, far from southern commercial hubs where grocery resupply operations are based. As a result, the retailing of groceries becomes a notably more costly endeavor compared to similar activities in southern regions (Government of Canada, 2015). The carbon footprint of Canadian market lettuce flown 2,000 km, assuming standard carbon intensity factors for long-haul air freight (Howitt et al., 2011), is 1.6 kg $CO_2$e/FU. This would make CE-UA comparable to the market average in Yukon but still much higher than conventional sources in Northwest Territories or Nunavut.




| Province/Territory | kg CO2e/FU (% of Canadian Market) | % of electricity from fossil sources |
|---|---|---|
| Prince Edward Island (PE) | 0.52 (80%) | 0.5% |
| Quebec (QC) | 0.61 (94%) | 0.3% |
| Manitoba (MB) | 1.01 (156%) | 0.1% |
| Ontario (ON) | 1.32 (203%) | 7.3% |
| Newfoundland and Labrador (NL) | 1.5 (245%) | 3.6% |
| British Columbia (BC) | 2.01 (309%) | 4.5% |
| Yukon (YK) | 2.59 (398%) | 20.0% |
| Northwest Territories (NT) | 4.88 (750%) | 51.0% |
| New Brunswick (NB) | 4.89 (752%) | 30.0% |
| Saskatchewan (SK) | 11.31 (1740%) | 81.0% |
| Alberta (AB) | 12.178 (1873%) | 90.1% |
| Nova Scotia (NS) | 13.82 (2126%) | 76.0% |
| Nunavut (NU) | 16.56 (2547%) | 100.0% |

**Figure 3.4:** kg $CO_2$-eq/kg edible lettuce GWP of CEA across Canada. Note that Quebec stands in for the Montreal CE-UA system. Table on the right shows the results for each province and territory and the percentage of electricity from fossil sources.

### 3.3.2 Land Use (LU)

Figure 3.5 shows the results, and Table 3.3 shows the contribution analysis for LU impacts on our systems. Canadian market lettuce requires 0.30 $m^2a$ crop eq/FU, compared to 0.15 $m^2a$ crop eq/FU for CE-UA-MTL. CE-UA-BC and CE-UA-AB exhibit lowered values of 0.056 $m^2a$ crop eq/FU and 0.087 $m^2a$ crop eq/FU, respectively. Thus, CE-UA appears to have LU benefits over conventional sourcing, irrespective of production location.

Approximately 95% of potential LU impacts for CE-UA originate from electricity production in MTL, AB, and BC. The main driver is the extensive land occupation and transformation needed to accommodate the infrastructure demands of generating electricity (hydropower in QC and BC, fossil fuels from oilsands in AB). Romeo et al. (2018) highlight that hydroponic systems depend more on materials such as plastic and metals for the structural frame, hence requiring land for mining operations.

Conversely, the results from conventional domestic OF and GH systems are mainly linked to the direct occupation of agricultural land and transformation for electricity facilities generation, while OF imported is mainly driven by the direct land occupation, nonetheless has substantial indirect LU related to transportation lorry from energy delivery. The combination of direct land occupation and low yields leads to elevated LU, exacerbated by the lengthy cold periods of the year when the land is unused (Goldstein et al., 2016a). These findings highlight the divergent pathways through which different cultivation methods influence land utilization.

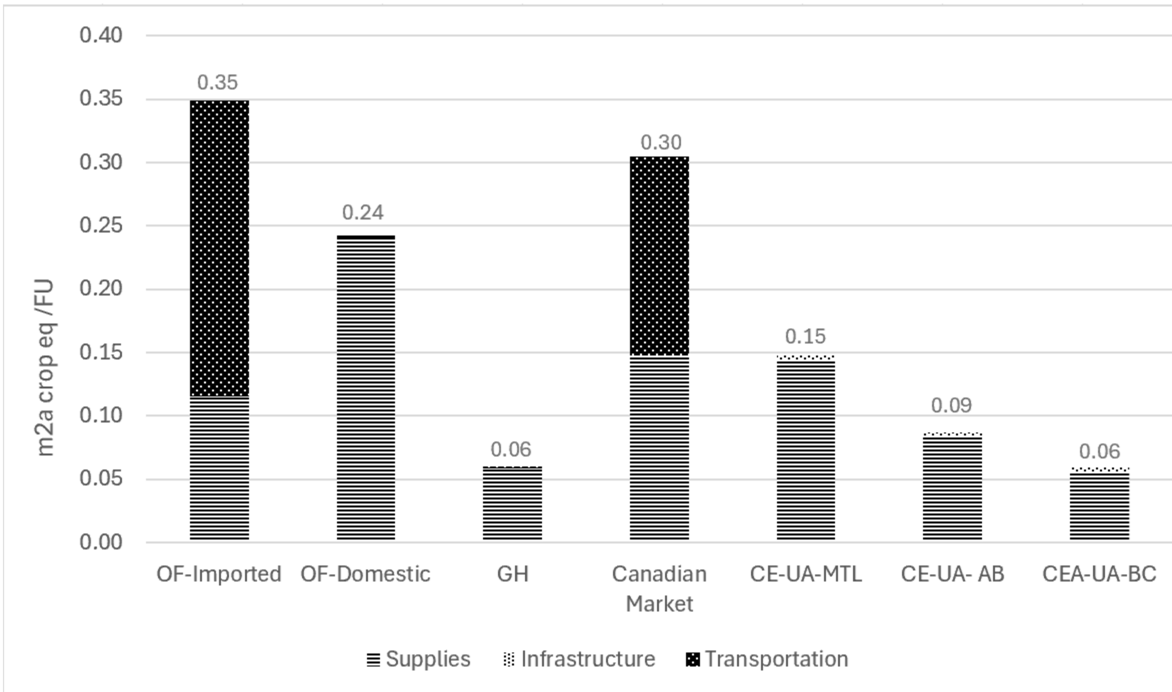



**Figure 3.5:** Land Use impact category results from CE-UA and Canadian market

**Table 3.3:** Key drivers of LU

| Farm System | Contribution by category | Key Drivers |
|---|---|---|
| **OF-Import** | 33.05% Supplies<br>66.95% Transportation | *land use 31%*<br>*transport 67%* |
| **OF-Domestic** | 99.38% Supplies<br>0.62% Transportation | *land use 92%, nutrients 7%, seeds 1%*<br>*transportation 1%* |
| **GH** | 97.5% Supplies<br>2.5% Transportation | *land use 92%, compost 3%, nutrients 2%*<br>*transport 2%* |
| **Canadian Market** | 48.43% Supplies<br>51.62% Transportation | *land use 43%, energy 2% compost 2%, nutrients 1%*<br>*transportation 52%* |
| **CE-UA-MTL** | 97.25% Supplies<br>1.74% Infrastructure<br>1.01% Transportation | *energy 97%*<br>*hydroponic 2%*<br>*transport 1%* |
| **CE-UA-AB** | 95.4% Supplies<br>2.91% Infrastructure<br>1.69% Transportation | *energy 95%*<br>*hydroponic 2%*<br>*transport 2%* |
| **CE-UA-BC** | 93.25% Supplies<br>4.27% Infrastructure<br>2.48% Transportation | *energy 93%*<br>*hydroponic 4%*<br>*transport 2%* |

*** OF, GH, and Canadian Market supplies include: energy, nutrients, water, seeds, and land use*

*** CE-UA supplies include: energy, water, and nutrients*

*** CE-UA Infrastructure include: container infrastructure, hydroponic system, and seedling room*

### 3.3.3 Water Resource Depletion (WRD)

By controlling environmental conditions and using hydroponics, CE-UA uses water much more efficiently than conventional cultivation methods, which are subject to dissipative losses and do not utilize water recapture and recycling. In the Canadian market, lettuce production typically requires 0.033 $m^3$eq/FU (0.03 $m^3$eq/FU from OF and 0.013 $m^3$eq/FU in GH cultivation), whereas CE-UA demonstrates a significantly lower requirement of 0.0028 $m^3$eq/FU. This stark difference of 11.5 times highlights CE-UA systems' superior water use efficiency.

These CE-UA findings align with existing studies, such as those referenced in Martin et al. (2023), which report water use ranging from 0.00050 to 0.016 $m^3$ per kg of edible produce.

Figure 3.6 underscores the stark discrepancies between CE-UA and conventional agriculture, particularly under intensified water scarcity considerations and varying country characterization factors. The characterization factor, sourced from lifecycleinitiative.org, delineates the relative environmental impact concerning water scarcity (Ansorge & Beránková, 2017). In the US, this factor exceeds Canada's, shedding light on their divergent impacts on water resource depletion. Consequently, FU production plays a significant role in water resource depletion within the Canadian market, which is influenced by increased water demand per FU and the substantial portion of Canadian market production originating from the US. AWARE method for WRD factors in regional water scarcity, accounting for remaining water availability within a watershed after addressing human and aquatic ecosystem needs. With drought conditions in California, the source of Canadian market lettuce, imported produce faces more significant WRD implications than domestic agriculture. Moreover, CE-UA's lower water demand per FU contributes to more favorable WRD outcomes (0.028 $m^3$eq/FU) compared to the Canadian Market (0.97 $m^3$eq/FU), signaling significant water-saving potential and a 48.5 times reduction in WRD compared to conventional practices.

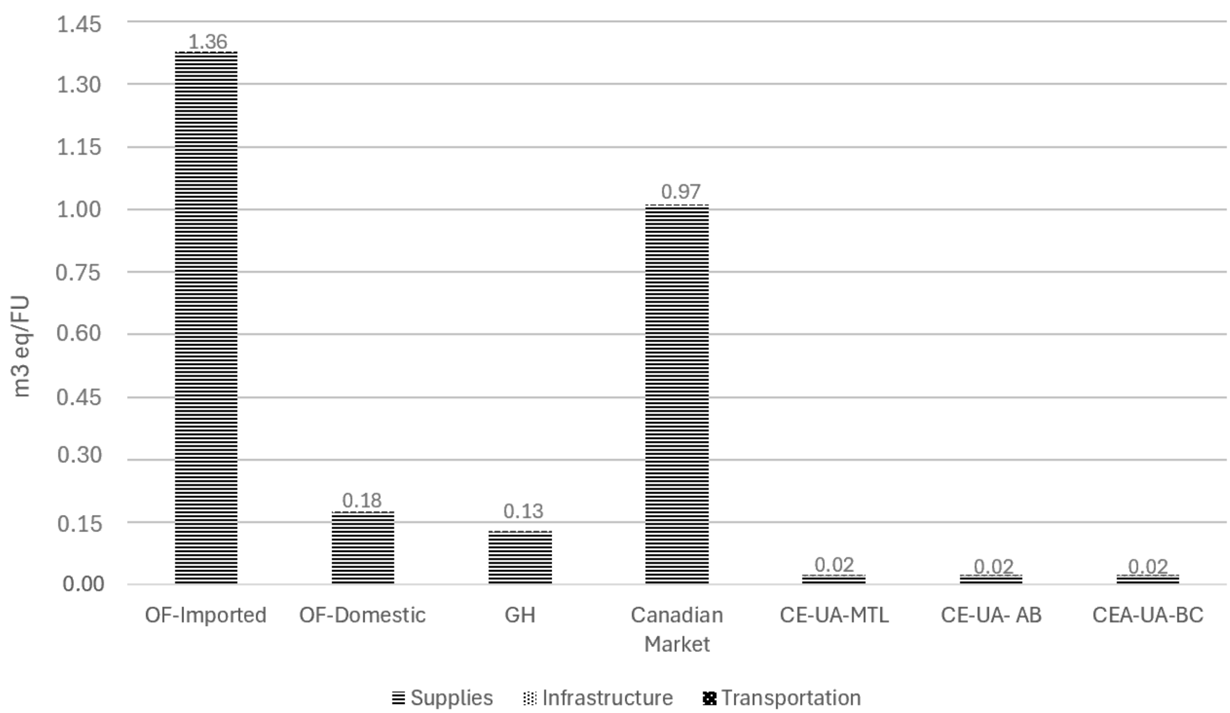



**Figure 3.6:** WRD impact category results from CE-UA and Canadian Market

Table 3.4 shows water usage by various processes for each production system. Naturally, WRD impacts for OF systems are driven by direct irrigation use (97-99% of WRD results). More water-efficient systems are split between direct irrigation and indirect water used to produce energy. For GH production, irrigation accounts for 50%, and water used in fossil fuel extraction accounts for 49%. WRD results for CE-UA systems in BC and MTL are predominantly attributed to hydroelectricity production. Although the water utilized for hydroelectricity generation is not directly consumed, its extraction for electricity production significantly impacts ecosystem functioning and competes with other crucial water uses. Even though the WRD from CE-UA in AB results are the same as in MTL and BC and come from the same category (supplies), the key drivers are distributed differently. In CE-UA-AB, the energy grid mainly comes from fossil sources, and the main contributors are the flow between water and electricity production.

**Table 3.4:** Key drivers of WRD

| Farm System | Contribution by category | Key Drivers |
|---|---|---|
| **OF-Import** | 99.94% Supplies<br>0.05% Transportation | *water use 99%, nutrients 1%* |
| **OF-Domestic** | 99.97% Supplies<br>0.02% Transportation | *water use 97%, nutrients 3%* |
| **GH** | 97.96% Supplies<br>0.03% Transportation | *water use 49%, energy 50%, nutrients 1%* |
| **Canadian Market** | 99.95% Supplies<br>0.05% Transportation | *water use 96%, energy 3%, nutrients 1%* |
| **CE-UA-MTL** | 99.14% Supplies<br>0.86% Infrastructure<br>0.19% Transportation | *energy 94%, water use 5%*<br>*hydroponic 1%* |
| **CE-UA-AB** | 95.57% Supplies<br>4.43% Infrastructure<br>0.19% Transportation | *energy 69%, water use 26%*<br>*hydroponic 5%* |
| **CE-UA-BC** | 99.23% Supplies<br>0.77% Infrastructure<br>0.19% Transportation | *energy 94%, water use 5%*<br>*hydroponic 1%* |

*** OF, GH, and Canadian Market supplies include: energy, nutrients, water, seeds, and land use*

*** CE-UA supplies include: energy, water, and nutrients*

*** CE-UA Infrastructure include: container infrastructure, hydroponic system, and seedling room*

## 3.4 Discussion

Our results suggest that CEA-UA can produce lettuce with multiple environmental benefits. In MTL (and QC), CE-UA can produce lettuce with similar or lower GWP impacts than the Canadian Market and substantially reduced LU and WRD impacts. Utilizing CE-UA in parts of Canada with fossil fuel-reliant electricity introduces trade-offs between elevated GWP impacts relative to conventional methods and LU and WRD benefits over the status quo. Our scenario analysis showed that GWP results are susceptible to the energy grid because of the high-energy demands of CE-UA. Thus, designers and operators of CE-UA systems should focus on improving the energy efficiency of these systems and strategic siting with low-carbon energy sources. Below, we discuss how CE-UA can be made more climate-friendly in different regions of Canada, how CE-UA can play a role in food access, and future research directions.

### 3.4.1 Different energy scenarios

Martin et al. (2023) emphasize the importance of electricity sources for CE-UA systems, showing that renewable energy can reduce GHG emissions. However, selecting electricity sources may have trade-offs, necessitating careful consideration. Regional electricity variations further complicate environmental performance estimation. Efforts to optimize energy efficiency through advanced technology are crucial (Martin et al., 2023). Barbosa et al. (2015) highlight that CE-UA lettuce's environmental footprint depends on electricity generation sources, emphasizing the role of renewable energy. While CE-UA systems may have lower environmental impacts than conventional imports, further improvements, especially in electricity use optimization, are needed.

### 3.4.2 Sustainable Practices for Farmers

To optimize sustainability in CE-UA, farmers can harness a range of cutting-edge technological advancements and strategic practices, with a primary focus on energy-efficient lighting systems such as LEDs, which have been widely recognized as the most efficient option for hydroponic setups (Kozai, 2013; Kozai et al., 2019; Both et al., 2012). Building on this foundation, some avenues exist for further enhancing LED technology to maximize energy savings and improve overall efficiency. A study by Shimizu et al., 2011, indicates that LED systems utilizing red and blue light exhibit superior power consumption and production efficiency compared to traditional fluorescent lamps, with monochromic red light demonstrating particularly effective outcomes for photosynthesis and growth in lettuce cultivation within CE-UA.

While the assessed CE-UA farm from this study already utilizes LEDs, there remain opportunities for optimization. One approach involves implementing innovative techniques like interplant lighting. LEDs are strategically positioned above culture panels to provide sideward and upward illumination, thereby optimizing light energy distribution to lower leaves and improving overall energy use efficiency. Additionally, improving the ratio of light energy absorbed by leaves relative to emitted lamp energy can further enhance efficiency. This can be achieved through well-designed light reflectors, adjustments in vertical lamp-to-plant distances, and optimization of plant spacing to accommodate growth (Kozai, 2013).

CE-UA farms can explore alternative lighting solutions with long lifespans and low energy consumption, such as induction lighting or plasma lights, which offer high energy efficiency and a broad spectrum of light conducive to plant growth (Hao et al., 2012; Jokinen et al., 2012). Moreover, integrating solar-powered lighting systems, supplemented by solar panels, presents an opportunity to reduce reliance on grid electricity and lower the overall carbon footprint of hydroponic operations. By continually innovating and refining lighting technologies, CE-UA farms can optimize resource use, minimize environmental impact, and enhance overall sustainability in urban agriculture. Diversifying energy sources by integrating renewable options such as solar panels and wind turbines presents an additional, promising avenue for reducing reliance on fossil fuels and mitigating environmental impacts (Martin et al., 2023).

Optimizing heating, ventilation, and air conditioning (HVAC) systems with advanced climate control technologies can yield substantial energy savings and create more conducive growing environments. By implementing precision climate control measures through high-efficiency HVAC systems, farmers can ensure optimal environmental conditions for plant growth while minimizing energy waste (Zhang et al., 2016). This approach enhances resource efficiency and contributes to overall operational sustainability. Furthermore, ongoing research and development efforts to address challenges such as airflow optimization in densely populated crop environments underscore the industry's commitment to continual improvement (Zhang et al., 2016). With careful integration of these technological advancements and best practices, CE-UA stands poised to emerge as a leading solution for sustainable urban agriculture, offering fresh produce while minimizing environmental impact.

### 3.4.3 CE-UA and supply-chain efficiency and Food Access

In the broader context of global food security and sustainability, addressing the significant environmental impact of food systems, including GHG emissions, deforestation, and water pollution, is paramount. Supply chain disruptions, like those experienced during the COVID-19 pandemic, emphasize the need for localized food production systems such as CE-UA to ensure resilience amidst shocks. CE-UA offers local food production and distribution advantages, potentially enhancing supply chain efficiency despite the concept of "food miles," which overlooks complexities in imported produce, which can involve energy-intensive technologies and loss of nutritional value throughout the supply chain.

Furthermore, CE-UA holds considerable promise in addressing food access challenges, particularly in remote regions with limited access to fresh produce. By enabling the direct provision of locally grown, nutrient-rich food to communities in need, CE-UA can significantly improve food equity and accessibility. By reducing dependence on long-distance air freight and storage, CE-UA can alleviate communities from inflated prices and nutritional losses typically associated with conventional supply chains. This underscores the transformative capacity of CE-UA in advancing food justice and enhancing food availability, particularly in northern territories and marginalized community areas where access to fresh produce is limited.

In addition to its transformative potential, policymakers are pivotal in fostering the widespread adoption of CE-UA technology, particularly in northern communities where food access challenges persist (Government of Canada, 2015). Recognizing the effectiveness of existing initiatives like the Nutrition North Canada (NNC) program in lowering prices on healthy food items, additional efforts are needed to address the enduring issue of high food costs in the North.

While the NNC subsidy helps enhance the affordability of groceries purchased through personal orders, there is a recognition that perishable goods are often best sourced locally due to quality control concerns. This is where CE-UA technology holds immense promise. However, the initial capital outlay required for establishing CE-UA operations, which includes investments in facilities, LED lighting, HVAC systems, and other essential components, remains a significant barrier.

To overcome this barrier, policymakers could provide financial support or incentives to reduce the initial investment burden on farmers and entrepreneurs interested in adopting CE-UA technology. By doing so, policymakers can stimulate greater uptake of CE-UA practices, thereby enhancing the efficiency and affordability of food production in northern communities.

Furthermore, alongside financial incentives, policymakers could establish training programs tailored to the specific needs of northern communities. These programs would facilitate the installation of CE-UA systems and ensure that residents receive the necessary training for maintenance and operation. By investing in financial support and training initiatives, policymakers can create an enabling environment for the widespread adoption of CE-UA technology, ultimately improving food access and security in northern communities.

### 3.4.4 Limitations and Recommendations for future research

Future research endeavors should address several critical areas to advance our understanding of CEA's environmental and societal impacts. These include expanding the scope beyond lettuce to encompass a broader range of crops, assessing the entire lifecycle of CE-UA operations, and conducting longitudinal studies to monitor operational efficiency and environmental performance over time. Additionally, incorporating regional climate and energy availability variations into modeling efforts is essential for accurately assessing CE-UA's environmental footprint across diverse geographic contexts. Moreover, future research should prioritize investigating sustainable agricultural infrastructure development practices, optimizing energy efficiency, and integrating renewable energy sources into CE-UA systems. By addressing these knowledge gaps, scholars can contribute to the ongoing evolution of CE-UA toward greater sustainability and resilience in the face of environmental challenges.

It is crucial to recognize that the applicability of these findings may vary depending on geographical factors, particularly considering the impact of WRD on results' variability from each region based on AWARE-CF. In methods like hydroponics, water-saving capabilities are even more pronounced, potentially reducing the water needed to grow certain crops by up to 11-12 times less water per FU. Furthermore, our study highlights the substantial contribution of infrastructure, namely the shipping container, to CE-UA GWP impacts. However, it is essential to note that assessing this infrastructure impact is subject to assumptions and methodological considerations, which may introduce limitations to the analysis. For example, assumptions regarding the lifespan of different infrastructure components can significantly influence overall system impact. While this study did not specifically address aspects like adaptive reuse of buildings and existing infrastructure, it warrants further exploration.

We did not use energy and water meters for this CE-UA case study since the assessed CE-UA company in MTL was at its start-up stage and has made some improvements since then. They did not have that in place at the time of inventory collection. With these meters, we could see the actual end uses of supplies, providing more accurate insights into resource consumption and efficiency. Uncertainty analysis could be used to assess influence of parameter uncertainty on directionality of results, but was not done here because of a lack of data on probability distributions of key parameters. Future research should consider incorporating eutrophication assessment into the analysis. CE-UA uses closed-loop water recycling to maximize nutrient recovery, which contrasts with OF, where a significant share of nutrients is often lost in runoff. Comparing the eutrophication performance between CE-UA and conventional farming systems would provide valuable insights into their environmental sustainability.

## 3.5 Conclusion

Efforts to mitigate climate change in agriculture require transitioning to farming methods with lower GHG intensity, implying fewer GHG emissions per unit of food produced. While CE-UA reduces the distance from farm to fork, it must be strategically deployed to ensure environmental sustainability, as our assessment shows, which is particularly relevant in Canada.

First, given Canada's cold climate, CE-UA requires substantial energy, ideally sourced from low-carbon sources. In provinces with carbon-intensive grids, combining CE-UA with on-site renewables is essential to ensure that local food production remains low-carbon. It is crucial to recognize that local food is not inherently low-carbon food. Second, regarding LU, the Canadian Market exhibits high land use pressure. However, CE-UA can have comparable predicted impacts, especially in regions where hydropower thirdly predominates in the electrical grid, while CE-UA farms consume minimal irrigation water compared to OF.

Despite these challenges, our analysis demonstrates that CE-UA can contribute to a more sustainable urban food system in some Canadian provinces. These high-tech systems often claim for their lower resource consumption and environmental pressure. The results reveal that the CE-UA-produced lettuce with GHG emissions of 0.61 kg $CO_2$-eq/kg edible is relatively carbon-competitive with market lettuce, contingent upon a larger share of renewable energy in the electricity mix. The source of electricity was found to significantly influence the system's environmental impacts, with a considerable portion stemming from electricity use in all categories. Despite potential improvements in GHG emissions with increased renewable energy use, trade-offs may exist, such as higher water use and resource depletion from the electricity generation process. The study underscores the need for further assessments of commercial systems and acknowledges the sensitivity of results to methodological choices.

While CE-UA showed lower resource use than conventionally sourced lettuce, additional research, and empirical evidence are necessary to evaluate CE-UA's sustainability comprehensively. Future studies should focus on longitudinal developments, viability, feasibility, and potential development scenarios to enhance resource and energy efficiency in CE-UA, considering regional contexts. Addressing substantial knowledge deficiencies concerning the consequences of climate change in agriculture is imperative for future research. This includes exploring the influence of yield variability on food production quantity and quality and ensuring healthy livestock for sustainable and nutritious food production.

## References

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., & Rounsevell, M.D., 2017. Losses, inefficiencies and waste in the global food system. Agricultural systems, 153, 190-200. https://doi.org/10.1016/j.agsy.2017.01.014

Ansorge, L., & Beránková, T., 2017. LCA water footprint AWARE characterization factor based on local specific conditions. European Journal of Sustainable Development, 6(4), 13-13. https://doi.org/10.14207/ejsd.2017.v6n4p13

Barbosa. G.L., Gadelha, F.D.A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., ... & Halden, R. U., 2015. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. International journal of environmental research and public health, 12(6), 6879-6891. https://doi.org/10.3390/ijerph120606879

Blom, T., Jenkins, A., Pulselli, R.M., & Van den Dobbelsteen, A.A.J.F., 2022. The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. Journal of Cleaner Production, 377, 134443. https://doi.org/10.1016/j.jclepro.2022.134443

Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., ... & Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). The International Journal of Life Cycle Assessment, 23, 368-378. https://doi.org/10.1007/s11367-017-1333-8

Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J., Derrible, S., & Guilbert, S., 2018. The Plant—An experiment in urban food sustainability. Environmental Progress & Sustainable Energy, 37(1), 82-90. https://doi.org/10.1002/ep.12712

Cowan, N., Ferrier, L., Spears, B., Drewer, J., Reay, D., & Skiba, U., 2022. CEA systems: the means to achieve future food security and environmental sustainability? Frontiers in Sustainable Food Systems, 6, 891256. https://doi.org/10.3389/fsufs.2022.891256

Canals, L.M.I., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., Edwards-Jones, G., & Hounsome, B., 2008. Life Cycle Assessment (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green beans. In RELU project REW-224-25-0044.

Dell'Anna, F., 2022. What advantages do adaptive industrial heritage reuse processes provide? An econometric model for estimating the impact on the surrounding residential housing market. Heritage, 5(3), 1572-1592. https://doi.org/10.3390/heritage5030082

Dong, Y., Hossain, M. U., Li, H., & Liu, P. (2021). Developing conversion factors of LCIA methods for comparison of LCA results in the construction sector. Sustainability, 13(16), 9016. https://doi.org/10.3390/su13169016

Ecoinvent Database, 2023. Introduction to the database. Knowledge Base. www.econivent.com

Fnais, A., Rezgui, Y., Petri, I., Beach, T., Yeung, J., Ghoroghi, A., & Kubicki, S., 2022. The application of life cycle assessment in buildings: challenges, and directions for future research. The International Journal of Life Cycle Assessment, 27(5), 627-654. https://doi.org/10.1007/s11367-022-02058-5

Foster, G., 2020. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. Resources, Conservation and Recycling, 152, 104507. https://doi.org/10.1016/j.resconrec.2019.104507

Gargaro, M., Murphy, R.J., & Harris, Z.M., 2023. Let-Us Investigate; A Meta-Analysis of Influencing Factors on Lettuce Crop Yields within Controlled-Environment Agriculture Systems. Plants, 12(14), 2623. https://doi.org/10.3390/plants12142623

Goldstein, B., Hauschild, M., Fernández, J., & Birkved, M., 2016a. Testing the environmental performance of urban agriculture as a food supply in northern climates. Journal of Cleaner Production, 135, 984-994. https://doi.org/10.1016/j.jclepro.2016.07.004

Goldstein, B., Hauschild, M., Fernández, J., & Birkved, M., 2016b. Urban versus conventional agriculture, taxonomy of resource profiles: a review. Agronomy for Sustainable Development, 36, 1-19. https://doi.org/10.1007/s13593-015-0348-4

Government of Canada, C.E.R., 2024. Canada energy regulator / Régie de l'énergie du Canada. CER. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/index.html

Government of Canada, Innovation, Science and Economic Development Canada, 2021. Innovative Solutions Canada: https://ised-isde.canada.ca/site/innovative-solutions-canada/en/enhancing-automation-controlled-environment-agriculture-farming

Government of Canada, Nutrition North Canada., 2015. Northern Food Retail Data Collection & Analysis by Enrg Research Group. https://www.nutritionnorthcanada.gc.ca/eng/1424364469057/1424364505951

Government of Canada, Statistics Canada, 2023b. Supply and disposition of food in Canada. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210005301&pickMembers%5B0%5D=2.153&cubeTimeFrame.startYear=2018&cubeTimeFrame.endYear=2022&referencePeriods=20180101%2C20220101

Hao, X., Little, C., & Khosla, S., 2012. LED inter-lighting in yearround greenhouse mini-cucumber production. Acta Hort., 956, 335-340. https://doi.org/10.17660/ActaHortic.2012.956.38

Hawes, J.K., Goldstein, B.P., Newell, J.P., Dorr, E., Caputo, S., Fox-Kämper, R., ... & Cohen, N., 2024. Comparing the carbon footprints of urban and conventional agriculture. Nature Cities, 1-10. https://doi.org/10.1038/s44284-023-00023-3

Howitt, O.J., Carruthers, M.A., Smith, I.J., & Rodger, C.J., 2011. Carbon dioxide emissions from international air freight. Atmospheric environment, 45(39), 7036-7045. https://doi.org/10.1016/j.atmosenv.2011.09.051

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., ... & Van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22, 138-147. https://doi.org/10.1007/s11367-016-1246-y

Institut de Recherche et de Développement en Agroenvironnnement (IRDA), 2017. Consommation d'énergie et émissions de gaz à effet de serre en production serricole au Québec. https://www.serres.quebec/download/publications/Energie/efficacite_energetique/RapportConsommation-energetique-et-reductions-des-emissions-de-GES-a-lhorizon-2020

International Organization for Standardization (ISO), 2006. ISO 14040:2006 Environmental management: life cycle assessment; Requirements and management. ISO. https://www.iso.org/standard/37456.html#:~:text=ISO%2014040%3A2006%20describes%20the,critical%20review%20of%20the%20LCA%2C

Jacquemin, L., Pontalier, P. Y., & Sablayrolles, C. (2012). Life cycle assessment (LCA) applied to the process industry: a review. The International Journal of Life Cycle Assessment, 17, 1028-1041.

Klöpffer, W., & Grahl, B. (2014). Chapter 3: Life Cycle Inventory Analysis . In John Wiley & Sons Editor, Life Cycle Assessment (LCA): A guide to best practice (pp.63-170 ). Wiley

Martin, M., Elnour, M., & Siñol, A. C., 2023. Environmental life cycle assessment of a large-scale commercial vertical farm. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2023.06.020

Mikosch, N., Dettmer, T., Plaga, B., Gernuks, M., & Finkbeiner, M. (2022). Relevance of impact categories and applicability of life cycle impact assessment methods from an automotive industry perspective. Sustainability, 14(14), 8837. https://doi.org/10.3390/su14148837

Nieuwlaar, E., 2004. Encyclopedia of energy life cycle assessment and energy systems. Elsevier BV, 647–654. https://doi.org/10.1016/B0-12-176480-X/00233-3.

Jayasundara, P.M., & Rathnayake, M., 2023. Environmental impacts and sustainability assessment of fruit and vegetable waste valorization through life cycle assessment (includes an overview of life cycle assessment from laboratory scale to industrial implementations and social & economic sustainability). Fruit and Vegetable Waste Utilization and Sustainability, 181-212. https://doi.org/10.1016/b978-0-323-91743-8.00010-1

Jensen, A., Mogensen, L., van der Werf, H.M., Xie, Y., Kristensen, H.L., & Knudsen, M.T., 2024. Environmental impacts and potential mitigation options for organic open-field vegetable production in Denmark assessed through life cycle assessment. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2024.02.008

Jokinen, K., Sarkka, L.E., & Nakkila, J., 2012. Improving sweet pepper productivity by LED interlighting. Acta Hort., 59-66. https://doi.org/10.17660/ActaHortic.2012.956.4

Kozai, T., 2013. Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proceedings of the Japan Academy, Series B, 89(10), 447-461. https://doi.org/10.2183/pjab.89.447

Kozai, T., Niu, G., & Takagaki, M. (Eds.), 2019. Plant factory: an indoor vertical farming system for efficient quality food production. Academic press. https://books.google.com/books?id=z-C7DwAAQBAJ

Leblanc-Laurendeau, O., 2020. Food insecurity in northern Canada: An overview. https://lop.parl.ca/sites/PublicWebsite/default/en_CA/ResearchPublications/202047E

Lee, U., Xu, H., Daystar, J., Elgowainy, A., & Wang, M., 2019. AWARE-US: Quantifying water stress impacts of energy systems in the United States. Science of the total environment, 648, 1313-1322. https://doi.org/10.1016/j.scitotenv.2018.08.250

Plawecki, R., Pirog, R., Montri, A., & Hamm, M.W., 2014. Comparative carbon footprint assessment of winter lettuce production in two climatic zones for Midwestern market. Renewable agriculture and food systems, 29(4), 310-318. doi:10.1017/S1742170513000161

Poore, J., & Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992. DOI:10.1126/science.aaq0216

Ritchie, H., & Roser, M., 2022. Environmental impacts of food production. Our world in data.

Romeo, D., Vea, E.B., & Thomsen, M., 2018. Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. Procedia CIRP, 69, 540–545. https://doi.org/10.1016/j.procir.2017.11.048

Shimizu, H., Saito, Y., Nakashima, H., Miyasaka, J., & Ohdoi, K., 2011. Light environment optimization for lettuce growth in plant factory. IFAC Proceedings Volumes, 44(1), 605-609. https://doi.org/10.3182/20110828-6-IT-1002.02683

Tourte, L., Smith, R.F., Murdock, J., & Sumner, D.A., 2017. Sample costs to produce and harvest iceberg lettuce—2017: Central coast—Monterey, Santa Cruz, and San Benito counties. University of California Agriculture and Natural Resources, Cooperative Extension and Agricultural Issues Center, UC Davis Department of Agricultural and Resource Economics, Davis, California.

Vatistas, C., Avgoustaki, D.D., & Bartzanas, T., 2022. A systematic literature review on controlled-environment agriculture: How vertical farms and greenhouses can influence the sustainability and footprint of urban microclimate with local food production. Atmosphere, 13(8), 1258. https://doi.org/10.3390/atmos13081258

Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., ... & Wernet, G., 2013. Overview and methodology: Data quality guideline for the ecoinvent database version 3. www.econivent.com

York University, n.d. Food Policy of Canada. Sustainable transportation: Challenges of food transport in Canada. https://foodpolicyforcanada.info.yorku.ca/goals/goal-5/sustainable-transportation/challenges-transport/#:~:text=With%20Canada's%20reliance%20on%20trucked,range%20(Klein%2C%201987).

Zhang, Y., Kacira, M., & An, L., 2016. A CFD study on improving air flow uniformity in indoor plant factory system. Biosyst. Eng., 147, 193-205. https://doi.org/10.1016/j.biosystemseng.2016.04.012

## Connecting Text to Chapter 4

In **Chapter 3**, we provide a manuscript for peer review. The paper comprises an abbreviated literature review of relevant and recent studies, outlines our research objectives, and presents findings on how the GWP, LU, and WRD results from the Canadian Market and CE-UA environmental impacts compare and how CE-UA performs in other provinces. **Chapter 4** provides a more in-depth discussion of our findings, key considerations, and potential future work based on our results.

# Chapter 4: Discussion

## 4.1 Contributions to Knowledge

Reimagining agricultural practices is imperative in the face of escalating urban populations and the pressing need for sustainable food production. Conventional agriculture faces multifaceted challenges, such as dwindling arable land, water scarcity, and environmental degradation, exacerbated by inefficiencies and waste within global food supply chains. Moreover, agriculture significantly contributes to GHG emissions and biodiversity loss, underlining the urgency for transformative shifts towards sustainable food systems (Poore & Nemecek, 2018; Ritchie & Roser, 2022; Alexander et al., 2017).

CE-UA has emerged as a potential solution to reduce the environmental pressures of food systems. It is capable of efficiently producing food while minimizing space and resource requirements. By optimizing growing conditions and mitigating environmental factors, CE-UA systems achieve remarkable yields while conserving water and using inputs of nutrients and other synthetic chemicals very efficiently (Barbosa, 2015; Gargaro et al., 2023; Cowan et al., 2022). However, it is important to note that CE-UA is not a means to reduce the reliance on these inputs; instead, it maximizes their efficiency. Nonetheless, the energy-intensive nature of CE-UA operations poses significant challenges, particularly regarding GHG emissions (Engler & Krarti, 2021).

Despite these challenges, CE-UA holds the potential to alleviate labor demands, particularly in light of Canada's agricultural labor shortages. This innovative approach promises to enhance food security and sustainability, especially in urban and remote areas (Kozai et al., 2019). This study aims to address knowledge gaps regarding the environmental performance of CE-UA, with a specific focus on the Canadian context. Considering Canada's reliance on imported produce and climatic adversities, investigating the feasibility of CE-UA within this framework becomes crucial (Government of Canada, 2021).

## 4.2 Sustainable Practices for Farmers

Considering the carbon-intensive nature of CE-UA, farmers aspiring to produce fresh food locally with minimal carbon footprints should adopt a series of proactive strategies aimed at reducing carbon energy usage. These strategies encompass a variety of interventions, ranging from the adoption of energy-efficient lighting systems to the installation of on-site renewable energy sources like solar panels. Moreover, integrating innovative engineering solutions to enhance overall energy efficiency within CE-UA operations can significantly reduce carbon emissions.

An important aspect to consider is the evolution of CE-UA farms over time. It is crucial to acknowledge the current stage of development of our case CE-UA farm in MTL, which is still in its startup phase. As technological advancements progress and operational practices refine, there is potential anticipation that this CE-UA farm will increase its efficiency, reduce its resource consumption, and lower the carbon intensity of the food it produces. This evolution highlights the dynamic nature of agri-business and underscores the potential for ongoing enhancements in sustainability metrics.

Furthermore, policymakers play a pivotal role in incentivizing the expansion of CE-UA farms, particularly in regions endowed with access to low-carbon energy sources. By providing targeted incentives and support mechanisms, policymakers can accelerate the deployment of CE-UA farms in strategic locations, thereby amplifying their positive environmental impact. This strategic approach not only fosters the expansion of sustainable agricultural practices but also contributes to broader efforts to mitigate environmental degradation and foster resilience in food production systems.

To optimize sustainability in CE-UA, farmers can harness a range of cutting-edge technological advancements and strategic practices, with a primary focus on energy-efficient lighting systems such as LEDs, which have been widely recognized as the most efficient option for hydroponic setups (Kozai, 2013; Kozai et al., 2019; Both et al., 2012). Building on this foundation, some avenues exist for further enhancing LED technology to maximize energy savings and improve overall efficiency. A study by Shimizu et al. (2011) indicates that LED systems utilizing red and blue light exhibit superior power consumption and production efficiency compared to traditional fluorescent lamps, with monochromic red light demonstrating particularly effective outcomes for photosynthesis and growth in lettuce cultivation within CE-UA.

While the assessed CE-UA farm from this study already utilizes LEDs, there remain opportunities for optimization. One approach involves implementing innovative techniques like interplant lighting. LEDs are strategically positioned above culture panels to provide sideward and upward illumination, thereby optimizing light energy distribution to lower leaves and improving overall energy use efficiency. Additionally, improving the ratio of light energy absorbed by leaves relative to emitted lamp energy can further enhance efficiency. This can be achieved through well-designed light reflectors, adjustments in vertical lamp-to-plant distances, and optimization of plant spacing to accommodate growth (Kozai, 2013). Furthermore, CE-UA farms can explore alternative lighting solutions with long lifespans and low energy consumption, such as induction lighting or plasma lights, which offer high energy efficiency and a broad spectrum of light conducive to plant growth (Hao et al., 2012; Jokinen et al., 2012).

Moreover, integrating solar-powered lighting systems, supplemented by solar panels, presents an opportunity to reduce reliance on grid electricity and lower the overall carbon footprint of hydroponic operations. By continually innovating and refining lighting technologies, CE-UA farms can optimize resource use, minimize environmental impact, and enhance overall sustainability in urban agriculture. Additionally, diversifying energy sources by integrating renewable options such as solar panels and wind turbines presents a promising avenue for reducing reliance on fossil fuels and mitigating environmental impacts (Martin et al., 2023).

Moreover, optimizing heating, ventilation, and air conditioning (HVAC) systems with advanced climate control technologies can yield substantial energy savings and create more conducive growing environments. By implementing precision climate control measures through high-efficiency HVAC systems, farmers can ensure optimal environmental conditions for plant growth while minimizing energy waste (Zhang et al., 2016). This approach enhances resource efficiency and contributes to overall operational sustainability. Furthermore, ongoing research and development efforts to address challenges such as airflow optimization in densely populated crop environments underscore the industry's commitment to continual improvement (Zhang et al., 2016). With careful integration of these technological advancements and best practices, CE-UA stands poised to emerge as a leading solution for sustainable urban agriculture, offering fresh produce while minimizing environmental impact.

### 4.3 Food Access and Equity

In regions grappling with food challenges, particularly in remote and marginalized northern territories and communities, access to fresh produce remains a persistent issue. However, Controlled Environment Urban Agriculture (CE-UA) emerges as a promising solution, offering the potential to address food insecurity and accessibility issues. Despite the significant costs and capital investment associated with CE-UA farms, policymakers have a crucial role in facilitating their accessibility and sustainability.

CE-UA technology, while not consistently low carbon, can provide much-needed food in areas lacking access to fresh produce. This underscores the urgency of prioritizing solutions that tackle food insecurity, especially in regions where conventional agricultural practices are impractical or economically unfeasible. One effective intervention avenue for policymakers is to provide financial support or incentives to reduce the initial capital outlay required for establishing CE-UA operations. By alleviating the financial burden on farmers and entrepreneurs, policymakers can stimulate greater uptake of CE-UA technology, particularly in regions facing significant challenges in accessing nutritious food.

Moreover, innovative and sustainable CE-UA solutions are needed to reduce capital and production costs. Policymakers should invest in research and development to support the creation of technologies and practices that enhance the efficiency and affordability of CE-UA operations. Advancements in automation, energy optimization, and resource utilization can lead to more cost-effective and environmentally sustainable CE-UA systems.

Furthermore, addressing the unique challenges faced by remote communities, especially in northern regions where food costs are excessively high due to long-distance transportation, is paramount. By promoting CE-UA adoption in these areas, policymakers can help mitigate reliance on imported food, enhance food security, and reduce environmental impacts associated with transportation emissions.

Supply chain disruptions, such as those experienced during the COVID-19 pandemic, underscore the need for localized food production systems like CE-UA to ensure resilience amidst shocks. CE-UA offers local food production and distribution advantages, potentially enhancing supply chain efficiency. By directly providing locally grown, nutrient-rich food to communities in need, CE-UA can significantly improve food equity and accessibility, particularly in remote regions with limited access to fresh produce.

To overcome barriers to CE-UA adoption, policymakers should provide financial support and establish training programs tailored to the specific needs of northern communities. These programs would facilitate the installation and maintenance of CE-UA systems, ultimately creating an enabling environment for widespread adoption. Through strategic policy interventions and support for innovation, policymakers can make CE-UA more competitive, accessible, and sustainable, thereby improving food access and security in northern territories and marginalized community areas.

## 4.4 Limitations and Recommendations for Future Research

In future research endeavors, it is crucial to incorporate several additional considerations to understand the environmental and societal impacts of CE-UA comprehensively. Firstly, it is essential to acknowledge that energy and water meters were not utilized for this CE-UA case study due to the company's early-stage operations. However, integrating these meters in future studies would provide invaluable insights into the actual end uses of supplies, allowing for a more accurate assessment of resource consumption and efficiency.

Furthermore, future research should also consider eutrophication as a critical factor. Compared with conventional OF, CE-UA's closed-loop water recycling maximizes nutrient recovery, where significant nutrient loss occurs through runoff. Therefore, future studies should explore and compare the performance of CE-UA and OF in terms of eutrophication potential, shedding light on the environmental benefits of CE-UA's nutrient management practices.

In addition to these considerations, future research endeavors should expand the scope of crop assessment beyond lettuce to encompass a more comprehensive range of crops. This broader focus will provide a more holistic understanding of CE-UA practices across various agricultural contexts.

Moreover, conducting longitudinal studies is essential to evaluate CE-UA operations over time beyond the startup phase. These longitudinal analyses will offer insights into the evolution of operational efficiency, environmental performance, and scalability of CE-UA practices.

Furthermore, it is imperative to adapt energy usage models for regional temperature variations across Canada. This adjustment will enhance the accuracy of environmental assessments by considering the specific energy requirements of CE-UA facilities in different climatic regions.

Additionally, incorporating food miles into all scenarios is crucial for comprehensively evaluating CE-UA's environmental footprint. Accounting for the distance food travels from production to end of life will enable a more nuanced understanding of transportation-related emissions and guide strategies to minimize carbon emissions throughout the supply chain.

Lastly, future research should prioritize exploring sustainable agricultural infrastructure development practices, optimizing energy efficiency, and integrating renewable energy sources into CE-UA systems. By harnessing innovative technologies and strategies, researchers can identify pathways to reduce energy consumption, mitigate greenhouse gas emissions, and enhance overall sustainability in CE-UA operations. Addressing these knowledge gaps and pursuing research initiatives to enhance sustainability and resilience in CE-UA will advance our understanding of its environmental and societal impacts. This collaborative effort will inform more effective policymaking, industry practices, and the development of resilient food production systems capable of meeting the challenges posed by environmental change.

## Connecting Text to Chapter 5

In **Chapter 4**, we discuss the overarching themes of our findings, offering further context for sustainable farming solutions. We explore the potential of CE-UA in addressing food access and equity in northern territories and communities. Additionally, we identify potential areas for future research expansion. **Chapter 5** summarizes the research outcomes and outlines our contributions to the existing knowledge base in our field.

## Chapter 5: Summary and Conclusion

Considering the burgeoning global population and the consequent rise in food demand, exploring sustainable approaches alongside conventional methods becomes imperative. CE-UA emerges not as a replacement but as a complementary solution to conventional agriculture, playing a pivotal role in meeting the escalating food demand. This study delves into the environmental impacts of CE-UA, with a specific focus on high-tech urban lettuce farming in Canada, aiming to provide comprehensive insights into its sustainability compared to conventional agriculture.

CE-UA offers promising solutions to optimize space utilization, increase crop yields, and minimize resource consumption. However, significant knowledge gaps exist in comprehensively assessing its environmental impacts, particularly concerning energy sourcing and geographical variations. To bridge this gap, we conducted a life cycle assessment of a shipping container CE-UA in Montreal, evaluating CE-UA sustainability across different Canadian provinces and climates.

Our findings reveal that in regions with low-carbon energy grids like Quebec, CE-UA demonstrates comparable or even lower GHG emissions, 0.61 kg $CO_2$-eq/kg, than conventional methods available on the Canadian market (0.65 kg $CO_2$-eq/kg). Notably, GH-grown lettuce within the Canadian market records slightly higher emissions (2.9 kg $CO_2$-eq/kg), indicating potential variability compared to conventional methods and CE-UA. The sourcing of electricity emerges as a critical determinant of environmental impacts within the CE-UA system, highlighting the significance of selecting low-carbon energy sources to shape overall sustainability profiles. Conversely, in regions with carbon-intensive energy grids, relying heavily on fossil fuels for electricity generation (i.e., coal, oil, and natural gas), such as Alberta, CE-UA can exhibit significantly higher emissions (12 kg $CO_2$-eq/kg), underscoring the importance of considering energy sources in evaluating environmental footprints. This study emphasizes the critical role of electricity sourcing in shaping the environmental outcomes of CE-UA, with scenarios powered by renewable energy sources showing notably lower emissions, underscoring the necessity of prioritizing low-carbon energy integration in CE-UA operations.

Our study highlights the substantial impact of electricity production on LU and WRD within CE-UA, particularly in regions relying on hydroelectricity, necessitating extensive infrastructure. While advancements in energy-efficient technologies within CE-UA facilities offer promise in mitigating these impacts by reducing energy infrastructure needs, it is crucial to note that CE-UA systems often exhibit superior resource utilization efficiency compared to conventional agriculture. Our findings reveal that CE-UA demonstrates lower LU and WRD impacts than the Canadian market. Specifically, CE-UA systems exhibit 11.5 times greater water use efficiency and 48.5 times lower WRD results than the Canadian Market. Regarding LU, CE-UA accounts for almost half of the impact observed in the Canadian market. LU primarily stems from the infrastructure associated with electricity plants rather than direct land use and transportation-related transformations, which is the same as for WU. These results underscore the potential of CE-UA to alleviate environmental pressures associated with conventional agricultural practices, emphasizing the importance of prioritizing sustainable practices and optimizing energy efficiency within CE-UA operations to foster a more resilient and environmentally conscious agricultural sector in Canada.

Our comprehensive assessment provides valuable insights into CE-UA lettuce production's environmental implications in Canada, identifying key factors driving environmental impacts and highlighting regional variations. To realize CE-UA's full potential in addressing food security and environmental sustainability, prioritizing low-carbon energy sources and considering regional factors in deployment strategies are essential. In conclusion, while CE-UA holds promise in contributing to a more sustainable urban food system in some Canadian provinces, additional research and empirical evidence are needed to evaluate its sustainability comprehensively. Future studies should focus on enhancing resource and energy efficiency, considering regional contexts, and addressing knowledge gaps concerning climate change impacts on agriculture. Through concerted efforts, CE-UA can emerge as a cornerstone of sustainable food production, paving the way for a more resilient and environmentally conscious agricultural sector.